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Piloted Simulation of an F-16 Flight Control System Designed Using Quantitative Feedback Theory

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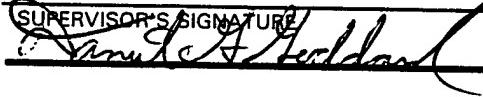
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1.0 Introduction

The Control Systems Development & Applications Branch of the Flight Control Division of Wright Laboratory, (WL/FIGS) has undertaken a program of research to determine the applicability of the Quantitative Feedback Theory (QFT) approach to designing control laws for a modern military flight control system. Quantitative Feedback Theory is a phrase, coined by Dr. Isaac Horowitz in 1979, used to identify the method he developed for designing robust control systems. QFT accounts for the structured parameter uncertainty in the plant, up front in the model specification. It also directly addresses performance specifications and allows one to limit over-design. Several good references exist for QFT [1,2,3,4].

The primary objective of this research effort is to implement a robust flight control system using QFT, and take the design through piloted simulation and ultimately flight test. The goals of this program are to examine and reveal the benefits of QFT as a robust control technique. Some of the reported benefits of QFT are:

1. The result is a robust design which is insensitive to structured plant variation.
2. There is one design for the full envelope (no need to verify plants inside the templates).
3. Any design limitations are apparent up front.
4. There is less development time for a full envelope design than standard point-by-point techniques.
5. One can determine what specifications are achievable early in the design process.
6. One can redesign for changes in the specifications quickly.
7. The structure of the controller is determined up front (and may be low order fixed compensators).

The vehicle chosen for this development was the NF-16D Variable Stability In-Flight Simulator Test Aircraft (VISTA F-16).

1.1 Overview

This report documents a portion of the QFT research program, specifically, the implementation of a QFT design on a piloted simulation of the VISTA F-16. The control law design was accomplished as a Master's thesis at the Air Force Institute of Technology [7]. Maj Scott Phillips, an F-16 pilot and control system engineer, designed the control laws as a follow on to a thesis by Reynolds [8].

This report documents the development of the piloted simulation, summarizes the simulations conducted, and presents the results of the simulations.

1.2 Objectives

The objectives for simulating this control law design on a piloted simulator are as follows:

1. To test Phillips' design against a non-linear, 6DOF, simulation truth model emphasizing stability across entire design envelope.
2. To validate the achievement of the stated performance specifications.
3. To obtain initial handling/flying quality feedback for the QFT design which includes handling/flying quality requirements a-priori in the design.
4. To simulate flight scenarios not included in the design by Major Phillips, in order to investigate the degree of robustness inherent in a MIMO QFT design.
5. To investigate and document the performance of Phillips' command limiting scheme.

2.0 Background

This project is part of a research program within the Control Systems Development & Applications Branch of the Flight Control Division of Wright Laboratory, (WL/FIGS) to develop the tools and techniques for designing robust control systems.

2.1 History

WL/FIGS has been pursuing QFT research since the late 70's. Graduate theses at the Air Force Institute of Technology sponsored by WL/FIGS included control law designs for models of the C-135, YF-16 CCV, STOL/F-15, AFTI/F-16, HARV F-18 and an electrohydrostatic actuator. With the development of a sophisticated QFT CAD package in 1992[9], the effort involved in QFT design declined dramatically. It made possible the design, implementation and flight test of a QFT based flight control system for the LAMBDA Unmanned Research Vehicle (URV), owned and operated by WL/FIGS. Since then, research has focused on developing robust control laws for the VISTA F-16 with an eye towards eventually flight testing such a QFT based robust flight control system.

QFT has many benefits as stated above, but QFT is particularly attractive to WL/FIGS because in designing a flight control system, it is desirable to:

1. Address all known plant variation up front.
2. Incorporate information on the desired output tolerances.
3. Maintain reasonably low loop gain (reduce the "cost of feedback").

This last item is important to avoid the problems associated with high loop gains, such as sensor noise amplification, saturation, and high frequency uncertainties. The basic QFT process is summarized below.

2.2 Robust Control Design

In any control system design, there is a plant, P , that one wishes to control (See Figure 1). In realistic plants, there exists structured uncertainty in the parameters that define the plant. For example, this uncertainty can take the form of changes in operating condition, measurement uncertainty, or physical changes in the plant. When using QFT, one takes into account the uncertainty in this plant by defining a set of linear-time-invariant (LTI) transfer functions (plants), $P=\{P_i\}$, $i=1, \dots, j$.

This set of plants is defined based upon the variation of parameters in the plant. If a plant has a parameter a that varies over some range, $[a_{min}, a_{max}]$, a number of plants, P_i , are specified, each based upon a different a_i so that the entire range of parameter variation is represented. This variation is represented by templates in the frequency domain.

The object of the QFT technique is to design a fixed compensator G , and fixed prefilter F , so that the system will be controlled within specifications for any $P_i \in P$.

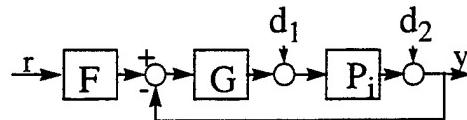


FIGURE 1. Feedback Control System

2.2.1 Specifications

Specifications for control systems are normally derived from the time domain figures of merit for a step response. The aim is to develop a *thumbprint*, which is an area that acceptable responses fall within such as is shown in Figure 2. The thumbprint specification is defined by an upper bound control ratio, $T_{RU}(s)$, and a lower bound control ratio, $T_{RL}(s)$. These control ratios are developed from the figures of merit such as peak overshoot, M_p , peak time, t_p , and settling time, t_s . See [1] Chapter 12 on designing control ratios from classical figures of merit.

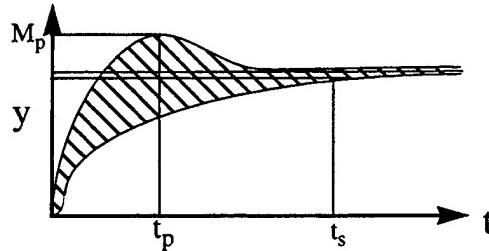


FIGURE 2. Thumbprint Specification

The time domain specifications are then translated into the frequency domain. The closed loop system is designed to have a frequency response between the upper and lower bounds as shown in Figure 3.

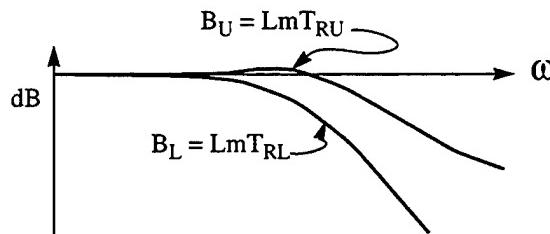


FIGURE 3. Frequency Domain Specifications

2.2.2 Control Law Design

The QFT design procedure begins with development of a set of templates. For each specified value of frequency, a template is developed by determining the frequency response of the various plants. This information is best envisioned by plotting all of the plant transfer

functions on a Bode plot and taking a slice, at a given frequency, of the Bode plots. At selected frequencies the gain and phase for each plant, P_i , are plotted on a Nichols chart to produce a template for that value of frequency. The template is usually taken to be the convex hull of this set of points (sometimes known as the rubber band method).

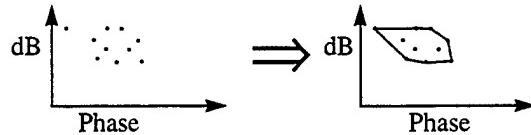


FIGURE 4. Templates

It is up to the designer to choose how many template frequencies are to be used in the design process. It is reasonable to choose 10 to 15 frequencies in the bandwidth of interest. The templates are used to generate bounds on a Nichols chart for the compensator design. When done on paper, this graphical method is quite time consuming. However, the advent of Computer Aided Control System Design (CACSD) software, specifically MIMO QCAD, has made this a painless process. This is discussed in the design section.

2.2.3 Stability Boundaries

A plant is chosen to be the “nominal” plant, P_o , (it is not important which one). To generate stability bounds, the templates are placed on a Nichols chart and moved around a stability margin contour. A constant M_p contour is frequently used to maintain both gain and phase margins. The template for each frequency is moved around the constant M_p contour, making sure no part of the template penetrates this contour. Marking where the nominal point on the template falls, for each frequency, a bound is created which is the stability bound. If the loop transmission, $l_o = GP_o$, for the nominal plant with compensation falls outside this bound, the system will be stable for all plants within the template.

2.3 Tracking Boundaries

To gain robust performance, it is necessary to generate performance bounds (tracking bounds). The templates for each frequency are placed on the Nichols chart where the closed loop variation in the plant is less than the variation allowed at that frequency by the tracking specifications. Marking where the nominal point on the template falls, for each frequency, a bound is created which is the tracking bound. If the loop transmission for the nominal plant with compensation falls above this bound, the variation in the response of the plant will be less than the allowed variation. The nominal loop is shaped to meet these bounds by cascade compensation.

It is important to note that the tighter the specifications are, the higher the tracking bounds will be. The higher the tracking bounds, the more gain will be required to meet the bounds. Remember that it is important to maintain reasonably low loop gain (reduce the “cost of feedback”) because there is noise in any system and a limited amount of power

available to control the system. This is the point in the design where the designer can see the trade off between robustness and the reality of design.

2.3.1 Disturbance Boundaries

To ensure the rejection of any disturbance, either external inputs or internal cross-coupling, boundaries are developed. The disturbance boundaries are developed in a similar manner to the tracking boundaries.

2.4 Controller

Based upon these bounds, the control engineer can design a cascade compensator, G , which meets these bounds as much as possible. Once the compensator is designed, the closed loop bode plots will be as close together as the tracking specifications, but they will not usually fall within the tracking specifications. A prefilter, F , is designed which brings the frequency response of the closed loop system within the tracking specifications.

Following these procedures, the control engineer should be able to design a control system which will control the plant within specifications for all specified plant variation. (See [1] Chapter 21 for a more complete explanation of the QFT design process.)

2.5 Phillips' effort

Major Scott Phillips, an F-16 pilot and control system engineer, designed control laws for the full subsonic flight envelope of the VISTA F-16 as a Master's thesis in 1994[7].

2.5.1 The VISTA F-16

The Variable Stability In-Flight Simulator Test Aircraft, or VISTA, went into operational service in January 1995 as the United States Air Force's newest in-flight simulator [5]. It was built from a production F-16D airframe, and incorporates production features from many different F-16 variants. The basic airframe was a Block 30, but included a large dorsal housing developed to carry avionics equipment for some foreign F-16s, heavy weight landing gear that eventually was incorporated on Block 50 aircraft, the digital flight control computer that went into Block 40s, and a heavier wing carry through structure developed for some F-16s delivered to the U.S. Navy for aggressor aircraft. It includes a complex custom-designed variable stability system to allow the VISTA's flight characteristics to be changed. Vista is a five degree-of-freedom aircraft, capable of simulating other aircraft at high subsonic speed, and pulling up to 7.33 Gs.

The VISTA F-16 was chosen because WL has flight test verified models of this aircraft and the QFT research program is proceeding with an eye towards eventually flight testing a control system designed using QFT.

The control law design addressed the subsonic flight envelope of the VISTA F-16 including some changes in aircraft configuration (external tank locations). These configuration

changes affect control response through varied center of gravity and moments of inertia. The design was accomplished as a SISO longitudinal loop and a MIMO lateral loop using MIMO QFT CAD software developed at AFIT [8]. The design incorporated pilot handling qualities within the specifications [6].

2.5.2 Longitudinal Design

A primary requirement of the control law design was that the resulting aircraft system handle well. This is defined as requiring Level 1 flying qualities per MIL-STD-1797A[6]. This standard describes proper pitch rate time response corresponding to Level 1 flying qualities. As Maj Phillips is an accomplished F-16 pilot, he chose not to control pitch rate (q) alone, but to combine q and g_{pil} (normal acceleration at the pilot's station) into a control variable denoted C^* . This variable is a hyperbolic combination of q and g_{pil} scheduled with dynamic pressure as shown in Figure 5. This definition varies from the linear combination found in most references. Imbedding handling qualities in the system through this prudent choice of control variable ensured that the performance specifications were met. The prefilter design flexibility subsequently allowed the response to be shaped for proper feel.

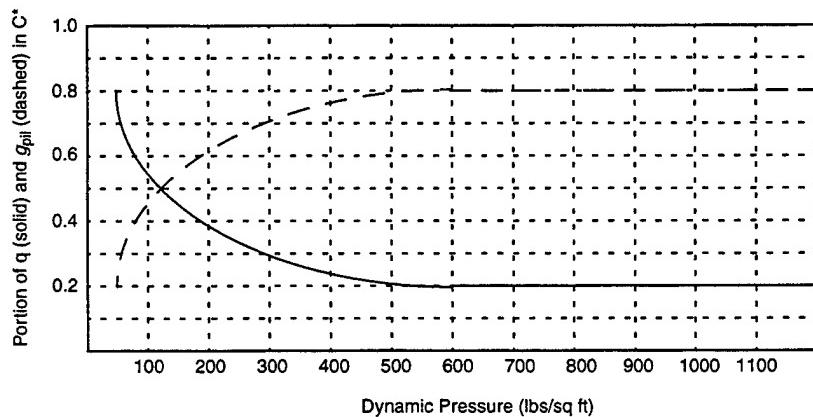


FIGURE 5. Schedule of Control Parameter C^*

The equations used to generate the constants of proportionality below 600 psf are:

$$K_q = 1 - \frac{143}{113 + \bar{q}} \quad (\text{EQ } 1)$$

$$K_{g_{pil}} = \frac{143}{113 + \bar{q}} \quad (\text{EQ } 2)$$

The longitudinal control input to the plant was elevator (symmetric tail deflection). Leading edge flaps are scheduled with angle of attack, α , in the baseline flight control system.

This is considered a configuration variable and left unchanged in the QFT based control system.

Specifications.

The design assignment required Level 1 flying qualities per MIL-STD-1797A[6]. The time domain tracking specifications from [6] are shown in Figure 6.

The QFT technique requires the designer to set frequency domain specifications based upon these time domain specifications. Although the standard specifications are for pitch rate instead of C*, and vary with flight condition, Phillips was able to develop the following model control ratios based upon the specifications:

$$T_{RU} = \frac{5(s + 0.7)^2}{(s^2 + 0.56s + 0.49)(s + 5)} \quad (\text{EQ 3})$$

$$T_{RL} = \frac{6}{(s + 2)(s + 3)} \quad (\text{EQ 4})$$

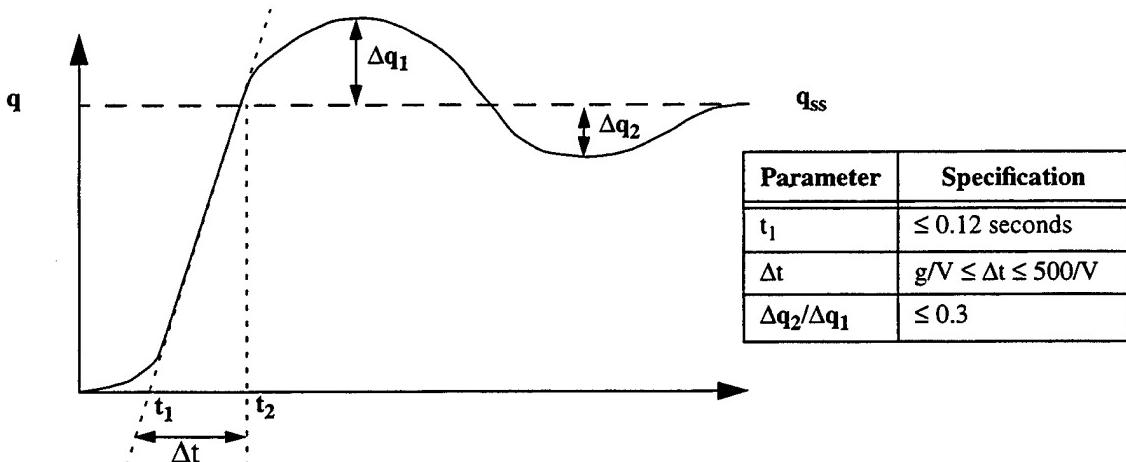


FIGURE 6. Time Domain Longitudinal Tracking Specification

These control ratios describe the frequency domain specifications as shown in Figure 7.

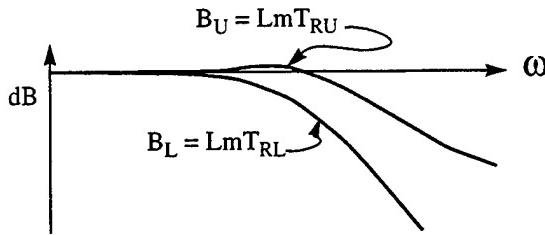


FIGURE 7. Frequency Domain Specifications

Along with these performance specifications, the military standard calls out additional performance margins and limits. A 30° phase margin and 6dB gain margin are specified for stability and are used directly in the design. To prevent departure from controlled flight, angle of attack, α , is limited to achieve 25° but not exceed 30° which is an F-16 specific requirement. To prevent damage to the airframe and pilot, load factor, g , is required to achieve 9g's but not exceed 9.45 g's.

Control Laws.

Based upon the models provided and the specifications develop, Phillips designed control laws covering the subsonic flight envelope of the VISTA/F-16. A suitable inner loop compensator, G_{C^*} , was found to be:

$$G_{C^*} = \frac{3.3(s + 1.7)(s + 3.5)}{s(s + 12)} \quad (\text{EQ } 5)$$

This compensator provides sufficient gain across the frequency band of interest to ensure that the closed loop transfer function does not vary more than the specifications allow. The closed loop transfer function is brought within the specification boundaries by designing a pre-filter to shape the response. In this case a simple lag function, F_{C^*} , brings the frequency response within specifications over the desired bandwidth.

$$F_{C^*} = \frac{3.5}{s + 3.5} \quad (\text{EQ } 6)$$

This compensator and pre-filter work very well for small signals across the envelope. However, they do not address the physical limits embodied in the additional handling quality specifications listed above. Since the actuators on the aircraft surfaces have deflection and rate limits, it is desirable to limit the control system to keep it from saturating. A schedule was developed for the pitch stick to limit the amount of C^* command allowed as a function of dynamic pressure. This pitch stick schedule is shown in Figure 8. It is very effective in preventing control surface saturation.

Even with this pitch stick schedule, however, the aircraft exceeds the angle of attack and load factor limits required. An additional schedule is then developed to limit the angle of attack and load factor. Angle of attack (α), rate of change of α ($\dot{\alpha}$), load factor (g), and

load factor onset (\dot{g}) are used as inputs to these schedules, which are shown in Figures 9 and 10. Detail concerning these schedules is contained in [7].

The resulting longitudinal flight control system is shown in Figure 11. The inner loop compensation is constant throughout the flight regime. Pilot stick characteristics are scheduled by dynamic pressure (q_{bar} or \bar{q}), and control input is limited by aircraft states.

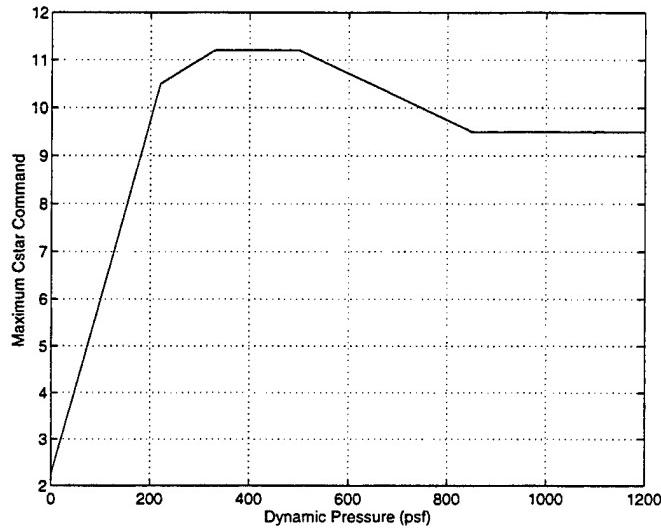


FIGURE 8. Schedule of Maximum Allowed Control Parameter C*

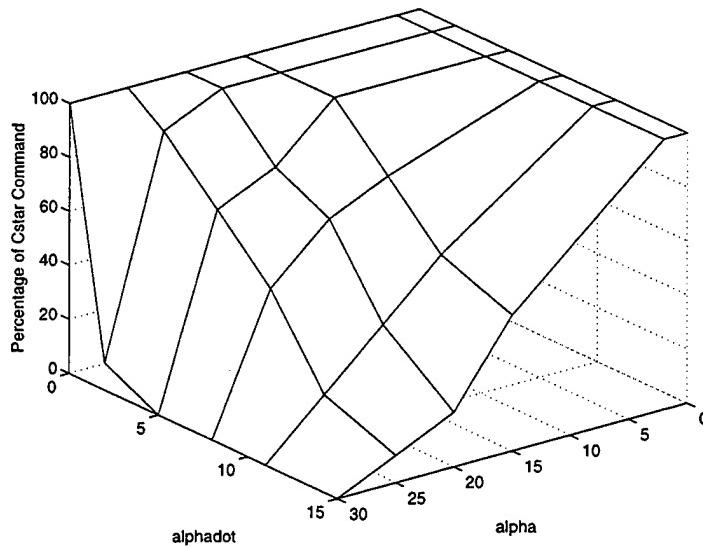


FIGURE 9. Schedule of Alpha Limiter

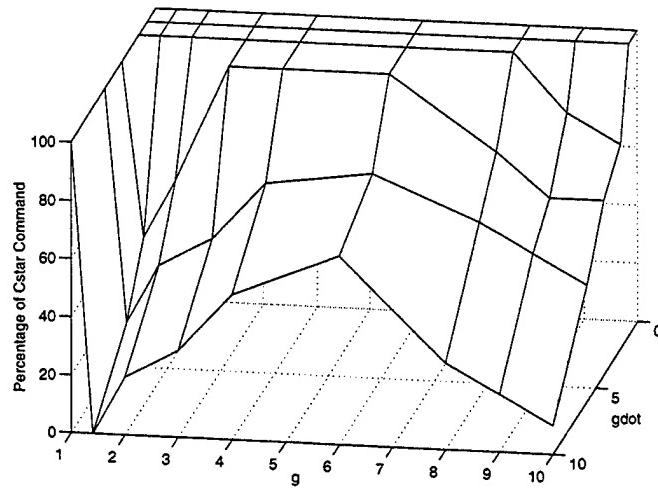


FIGURE 10. Schedule of g Limiter

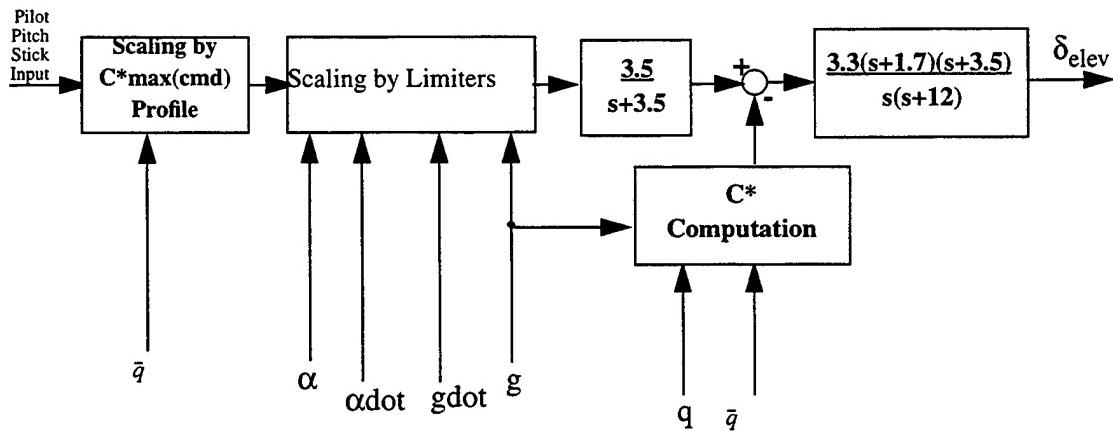


FIGURE 11. Longitudinal Flight Control System

Baseline Flight Control System.

In contrast to this control system designed with QFT, it is interesting to look at the baseline F-16 flight control system. The baseline from the VISTA/F-16 is the Block 40 DFCS. A diagrammatic description of the baseline flight control system, not including alpha lim-

iting, is shown in Figure 12. Though the baseline FCS controls from taxi through supersonic flight, it is still considerably more complex than the QFT FCS for the subsonic envelope. Most of the schedules shown are based on dynamic pressure and are piece-wise linear.

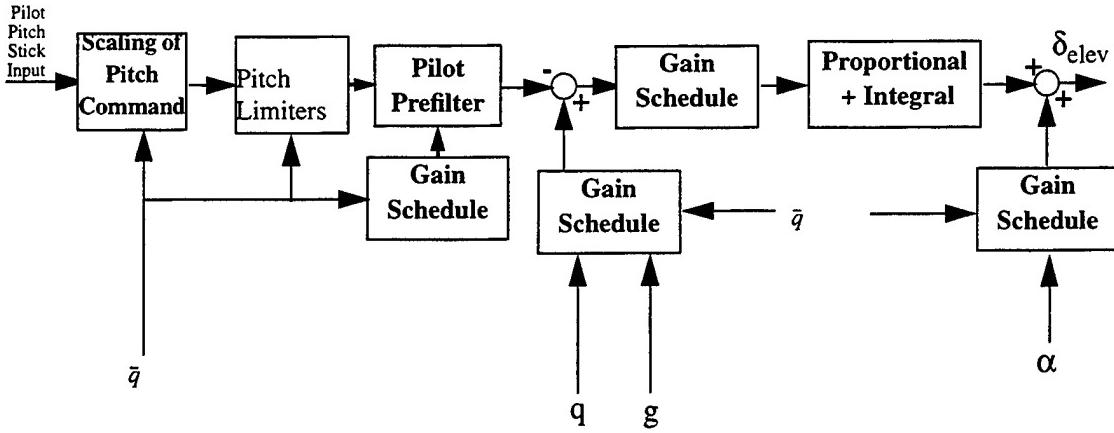


FIGURE 12. Baseline Flight Control System

Summary.

It was possible to develop a fixed compensator and scheduled command gradients that meet subsonic flight performance specifications. This system, designed using QFT, is considerably less complex than the baseline F-16 flight control system. The proof, however, is in implementation and pilot reaction which are described in the next chapter.

2.5.3 Lateral Design

A QFT based control system was also designed for the lateral directional channels of the VISTA/F-16. Roll rate, p , and sideslip angle, β , are the controlled variables in this 2×2 multiple input multiple output (MIMO) system. Before proceeding with the standard QFT design procedure, Phillips added a yaw damper to dampen the dutch roll mode. This was accomplished by feeding yaw rate, r , to the rudder command through a washout filter with the transfer function:

$$H_{wo} = \frac{s}{s + 0.3} \quad (\text{EQ 7})$$

The F-16 has three control surfaces used for the lateral channel, rudder, aileron and differential horizontal tail. Since only two variables are controlled, it is necessary to apportion the control surfaces to each channel. Rudder is used for the sideslip channel, controlling sideslip angle β , and aileron plus 0.294 differential tail is used for the roll channel, controlling roll rate p . The resulting aircraft model is as shown in Figure 13, where the lateral 3 x 2 MIMO plant includes the rudder actuator and yaw damper described above.

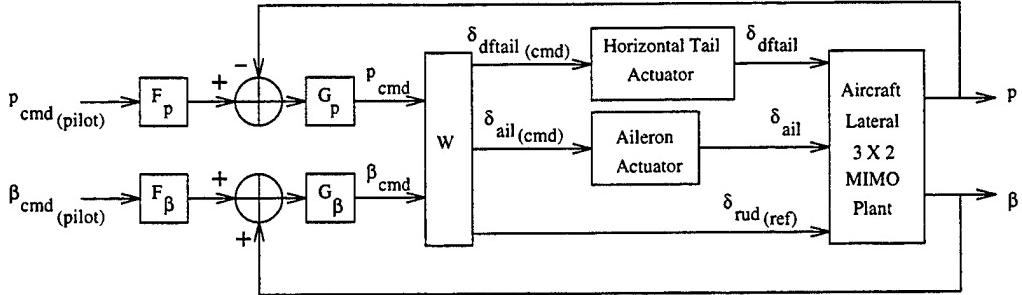


FIGURE 13. Lateral Control System Design Structure

Specifications.

MIL-STD-1797A specifies a minimum roll time constant of 1 second. Interpreted to require a settling time less than 4 seconds, this specification was the only one used to generate the roll channel upper and lower tracking control ratios:

$$T_{RU} = \frac{4(s+1)}{s^2 + 2s + 4} \quad (\text{EQ } 8)$$

$$T_{RL} = \frac{2.5}{(s+1.25)(s+2)} \quad (\text{EQ } 9)$$

The frequency response and time response of these functions for a step input are shown in [7]. The additional (and unfortunately more stringent) specifications of ability to roll through 360° in 2.8 seconds and ability to roll through 90° in 1 second were not used in the design phase, but evaluated in simulation.

There were no numerical specifications for the sideslip channel in MIL-STD-1797A, as it simply states the response will be smooth and not objectionable. Phillips required specifications to conduct the design and developed the following sideslip control ratios for his design:

$$T_{RU} = \frac{4(s+1)}{s^2 + 2s + 4} \quad (\text{EQ } 10)$$

$$T_{RL} = \frac{1}{(s+1)^2} \quad (\text{EQ } 11)$$

Control Laws.

Phillips used QFT to design the compensators for this system resulting in

$$G_p = \frac{0.125(s + 3)}{s} \quad (\text{EQ } 12)$$

$$F_p = \frac{3.5}{s + 3.5} \quad (\text{EQ } 13)$$

for the roll channel.

The sideslip channel required scheduling of the inner loop compensator so that

$$G_\beta = \frac{-100(s + 1.7)(s + 2)}{s(s + 60)} \quad (\text{EQ } 14)$$

for dynamic pressures below 150 psf and

$$G_\beta = \frac{-50(s + 1.7)(s + 2)}{s(s + 60)} \quad (\text{EQ } 15)$$

for dynamic pressures above 150 psf. The sideslip prefilter is

$$F_\beta = \frac{0.5}{s + 0.5} \quad (\text{EQ } 16)$$

The final lateral directional design is shown in Figure 14. The roll channel incorporates a constant, first order compensator and prefilter. The sideslip (yaw) channel has a second order compensator, first order prefilter and washout filter. The sideslip channel gain had to be scheduled because a fixed compensator would not provide adequate performance. This was evident early in the design from the size of templates.

Baseline Flight Control System.

A diagrammatic description of the baseline lateral flight control system is shown in Figure 15. This figure does not contain gun compensation, high angle of attack modes or any elements required for supersonic flight which are included in the actual baseline control system. It is slightly more complex than the control laws developed by Phillips. As in the longitudinal FCS, this structure is heavily dependent on gain scheduling.

Summary.

The baseline control system includes an aileron to rudder interconnect to provide turn coordination. Phillips' design does not address the inherent coupling of the roll and yaw channels, instead relying on sideslip feedback to coordinate the turn. To counter the reverse coupling, from rudder to roll axis, he limits the amount of sideslip command allowed. Phillips justifies this by noting the lack of use of the rudder in normal operation.

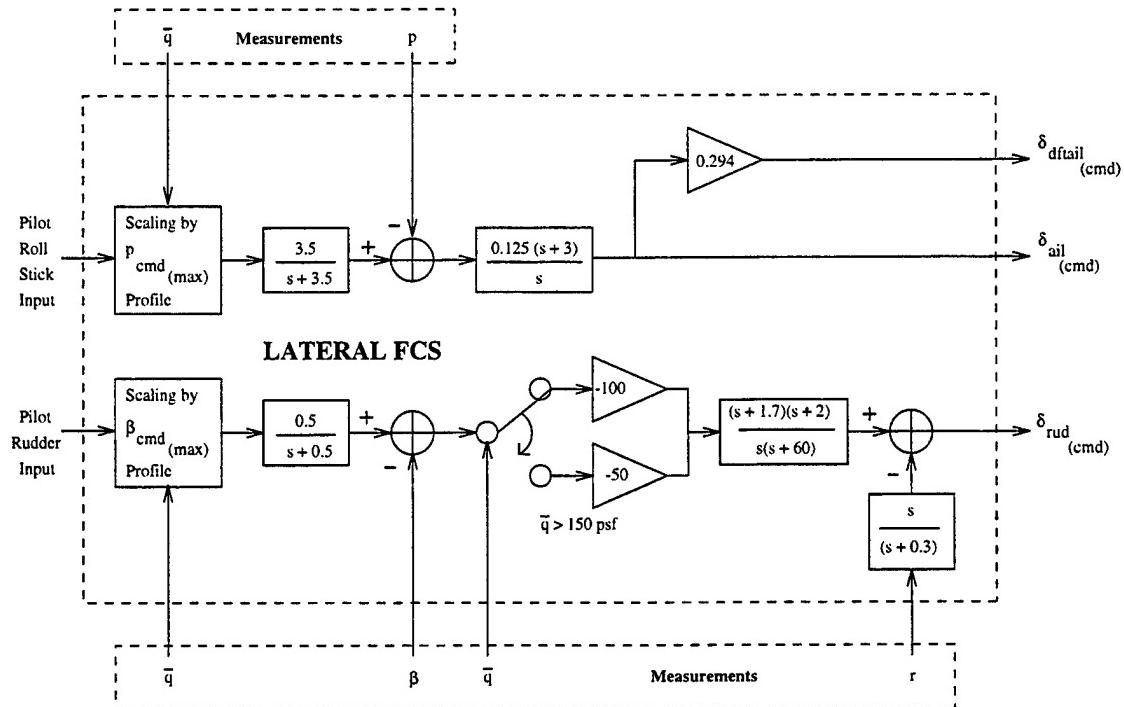


FIGURE 14. Lateral Control System Design

2.5.4 Conclusions

The control laws described above were designed by a single graduate student over a period of six months. As such, the scope of the problem had to be reduced to a subsonic, clean model (no landing gear or external stores). However, the results illustrate the efficiency of designing with QFT because the control law design problem is still a very significant venture. Assumptions made as to the structure of control desired by the pilot can only be proven through a piloted simulation program. Hence the reason for this effort.

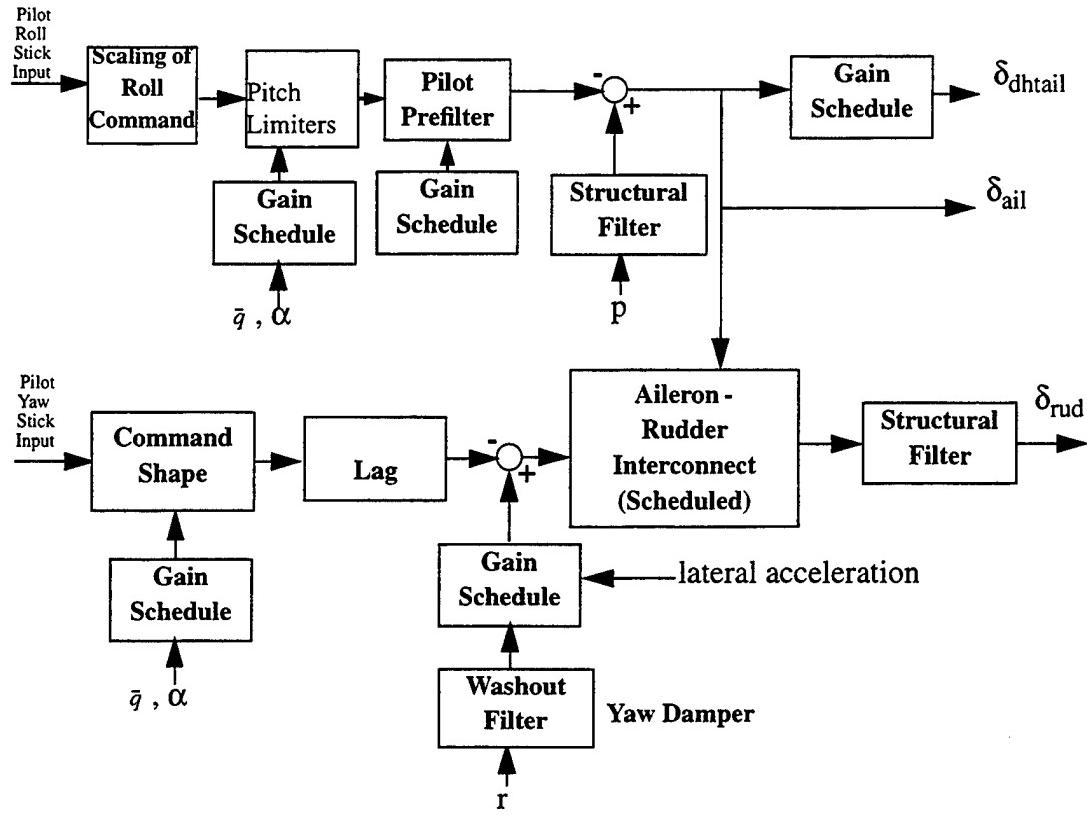


FIGURE 15. Baseline Lateral Flight Control System

3.0 Simulation Development

The handling qualities are being evaluated in a high fidelity, piloted simulation of the system. The simulation resides within the Large Amplitude, Multimode Aerospace Research Simulator (LAMARS) operated by The Control Integration and Assessment Branch of Wright Laboratory (WL/FIGD). LAMARS was designed for flying/handling qualities simulations. A cockpit similar to the F-16 cockpit is used with side-stick and throttle controls. Displays include standard aircraft instrumentation, a heads-up display (HUD) and out-the-window visual displays with a 160° horizontal field of view.

The aircraft model used in the simulation is a nonlinear, full-envelope aerodynamic model of the NF-16D Variable Stability In-Flight Simulator Test Aircraft (VISTA F-16). This model has been verified in previous programs through extensive comparison to flight test data. Logic emulating the Block 40 digital flight control system (DFCS) in the standard simulation is replaced by equivalent logic implementing the QFT based control laws in digital form at 50Hz. It takes force inputs from the stick and pedals and provides commanded deflection outputs (in degrees) to the actuators. It also includes angle of attack (AOA) and g limiting as well as AOA and g rate limiting, all consistent with the limiting which occurs in the Block-40 FCS.

4.0 Simulations

Simulations were conducted according to the simulation test plan in Appendix A. The QFT based control laws were evaluated in two phases. Phase I, stability tasks, included stick doublets and loaded rolls. Maximum stick doublet maneuvers were performed with an objective of achieving second order transient response with no overshoot, and minimal negative effect of secondary parameters (Mach, etc.) as compared to the Block-40 DFCS. Velocity vector rolls (loaded rolls) were performed with an objective of achieving angle-of-attack/sideslip angle response similar to the Block-40 DFCS. Dynamic stability throughout the maneuver was a basic requirement for these tasks.

Flight conditions varied from 0.3 Mach at 12,000 ft. (dynamic pressure, or \bar{q} , of 83 psf.) to 0.9 Mach at 10,000 ft. (\bar{q} of 825 psf.) Configuration variations included variations in the number of external fuel tanks (0, 1, or 2 tanks). It was apparent from Phase I maneuvers that the configuration variations did not have any dramatic effect on performance, hence, the remainder of the simulations were flown with a clean aircraft.

Phase I simulations were used to validate the simulation and identify any deficiencies that needed to be corrected. The simulation was properly designed according to the initial requirement of replacing the Block 40 control mechanization with the QFT control laws. This proved to have one flaw. The Block 40 flight control system uses leading edge flaps as a function of angle of attack. During the QFT design this was considered as a configuration variation and not a control surface, so the QFT design did not control leading edge flaps and it was assumed the leading edge flap control would remain unchanged. Within the simulation, however, the leading edge flap control is contained within the Block 40 flight control module. This resulted in the leading edge flaps being trimmed to the proper initial condition and remaining fixed for the QFT simulations. The leading edge flap control in the baseline control system was reconnected, and the yaw channel code error corrected and the Phase I simulations reaccomplished, so that final simulations were conducted with a valid model which included the Block 40 leading edge flap schedule.

Phase II incorporated positioning, gross acquisition and fine tracking tasks. Pitch, bank, and heading angle capture maneuvers were performed with the objectives of evaluating handling qualities and identifying maneuverability limitations and pilot-induced oscillation (PIO) tendencies. Multichannel gross acquisition maneuvers were performed to check handling qualities during elevated load factors and short-term response characteristics for aggressive pointing. Longitudinal and lateral HUD tracking were used to check handling qualities, feel system and control sensitivity characteristics in a tight, closed-loop tracking task. This was also intended to expose pitch bobble or PIO tendencies. An air-to-air fine tracking task was used to check the pilot's ability to gun track a target aircraft and expose short term longitudinal and lateral handling qualities deficiencies.

A third phase of simulations was planned to follow the standard handling qualities tasks listed above to investigate off-design robustness. Simulations incorporating alternate center of gravity locations and increased turbulence were to be conducted and compared with the Block 40 F-16 flight control system performance. These simulations were intended to illuminate the benefits of designing flight control systems with a robust control design technique. The simulations were not conducted due to time and funding constraints.

5.0 Results

Initially, Phase I simulations were performed over a two day period. Pilot comments and ratings were recorded and are attached in Appendix B. Simulation variables were saved to disk for post simulation analysis which revealed the lack of leading edge flap control, and a code error in the yaw channel software. Most Phase I simulations were reaccomplished along with the Phase II simulations over another two day period. Changing the aircraft configuration by adding external fuel tanks proved to have little effect on the aircraft response during the first test series. Therefore, in the second series, all simulations were run with a clean aircraft.

5.1 Phase I, Stability Tasks

Phase I, stability tasks, included stick doublets and loaded rolls. Maximum stick doublet maneuvers were performed with an objective of achieving second order transient response with no overshoot, and minimal negative effect of secondary parameters (Mach, etc.) as compared to the baseline DFCS. Dynamic stability throughout each maneuver was a basic requirement for these tasks. Comparison plots of the response during these doublet maneuvers are shown in Appendix C.

5.1.1 Pitch response

Figures 16 and 17 show the pitch doublet response at low \bar{q} . The pilot did not notice any difference between the baseline FCS and the QFT FCS pitch response. This could be attributed to the lack of motion in the simulation as pitch angle traces were similar for both systems.

Pitch rate, however, varied dramatically. The baseline FCS exhibits a large overshoot in pitch rate while the QFT FCS exhibits a well damped second order response. Analysis of the response shows the QFT FCS meets level 1 handling qualities for the pitch doublet maneuvers. The requirement is damping ratio greater than 0.36 and sufficiently fast rise time dependent on flight condition.

At high \bar{q} , the commanded variable is primarily load factor (normal acceleration). Figures 18 and 19 show the pitch doublet responses at high \bar{q} . Responses are very similar for both systems. One obvious deficiency with the QFT FCS is that the aircraft achieves a large negative load factor when commanded to pitch down. This was known beforehand as Maj Phillips made no attempt to limit negative load factor. This would have to be addressed in future work and would likely be handled with a limiting scheme similar to the current positive g limiter.

These plots do not show how well the system met the design specifications as the QFT FCS was based upon C^* as the control variable. The C^* response is shown in Figure 20 including dotted lines representing the tracking specifications. Even though this is a non-linear simulation, the specifications were met.

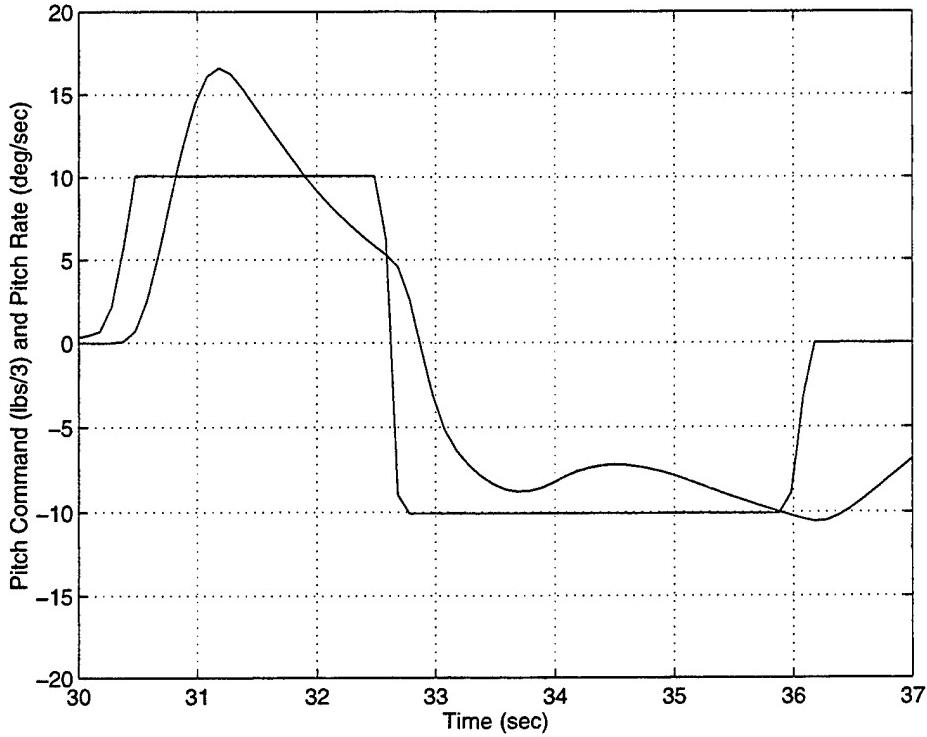


FIGURE 16. Baseline Pitch Response - Low \bar{q} - Mach .3, 10,000 ft.

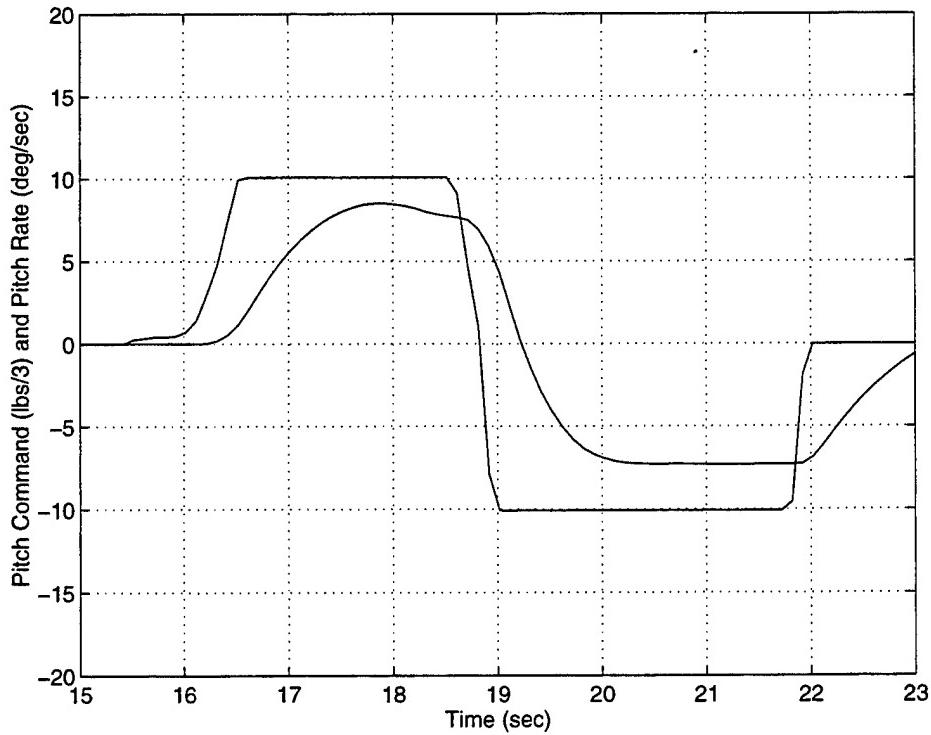


FIGURE 17. QFT Pitch Response - Low \bar{q} - Mach .3, 10,000 ft.

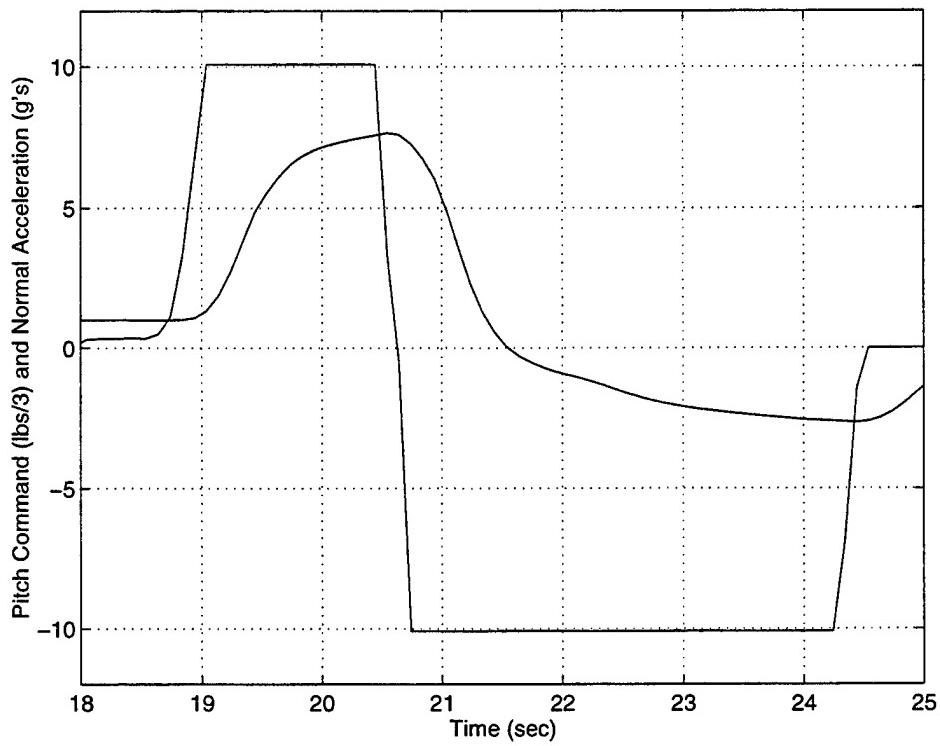


FIGURE 18. Baseline Pitch Response - High \bar{q} - Mach .9, 10,000 ft.

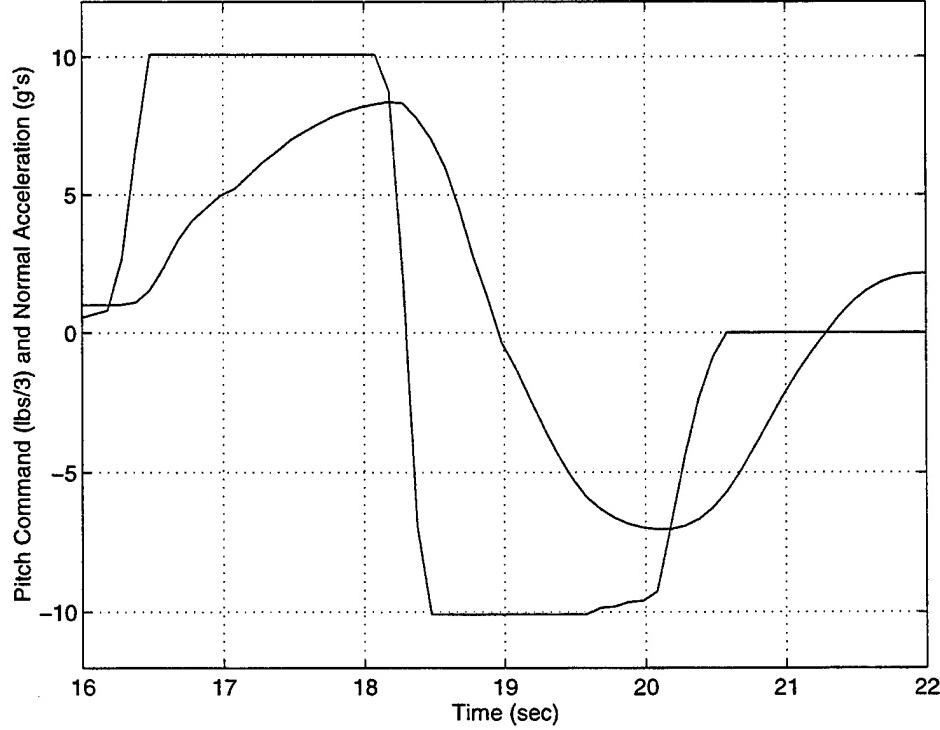


FIGURE 19. QFT Pitch Response - High \bar{q} - Mach .9, 10,000 ft.

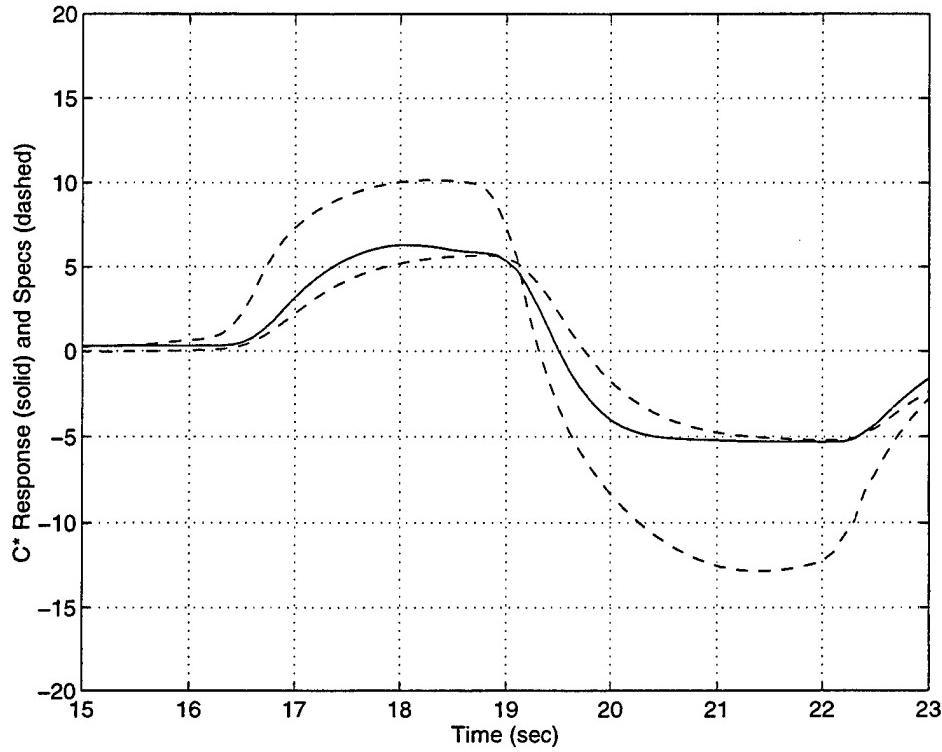


FIGURE 20. QFT C* Response - Low \bar{q}

5.1.2 Roll Response

The pilot noted that roll response was slower with the QFT control system but more controllable (stable). MIL-STD-1797A specifies a minimum roll time constant of 1 second. Interpreted to require a settling time less than 4 seconds, this specification was the only one used in the design. From Figures 21 and 22 it is apparent that the QFT FCS meets this specification. This is the least stringent specification, however.

A stricter measure of roll performance called out in the specification is time to roll through 90° . As shown in Figure 23, the QFT FCS is slow in comparison to the baseline and does not meet level 1 flying quality criteria in this area. This is not surprising as the design did not meet this criteria in the linear simulations of [7].

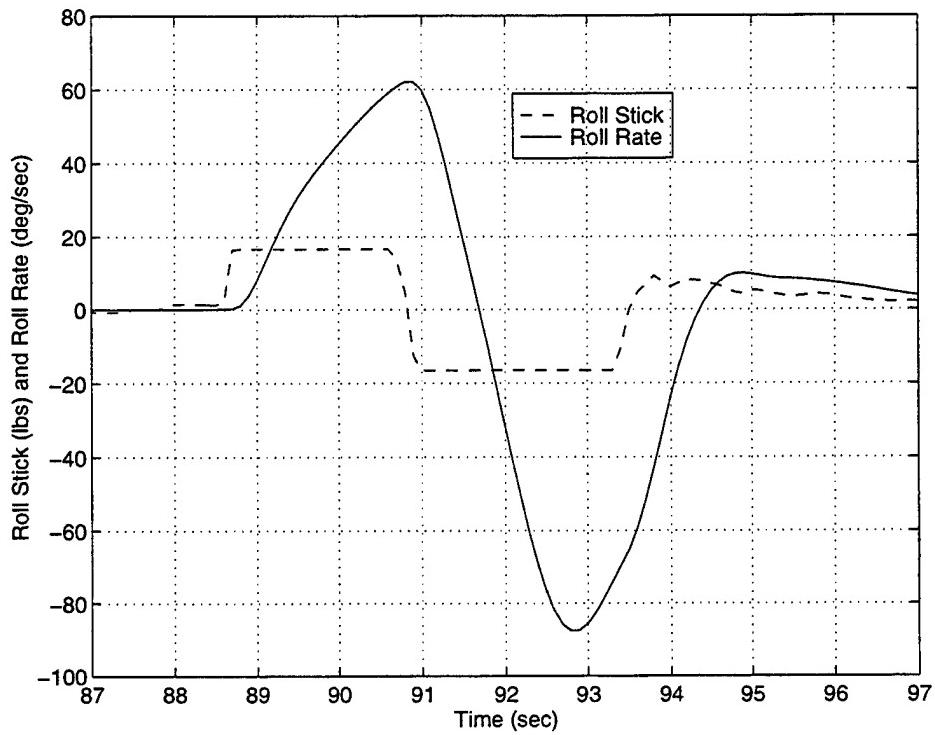


FIGURE 21. QFT Roll Response - Low \bar{q} - Mach .3, 10,000 ft.

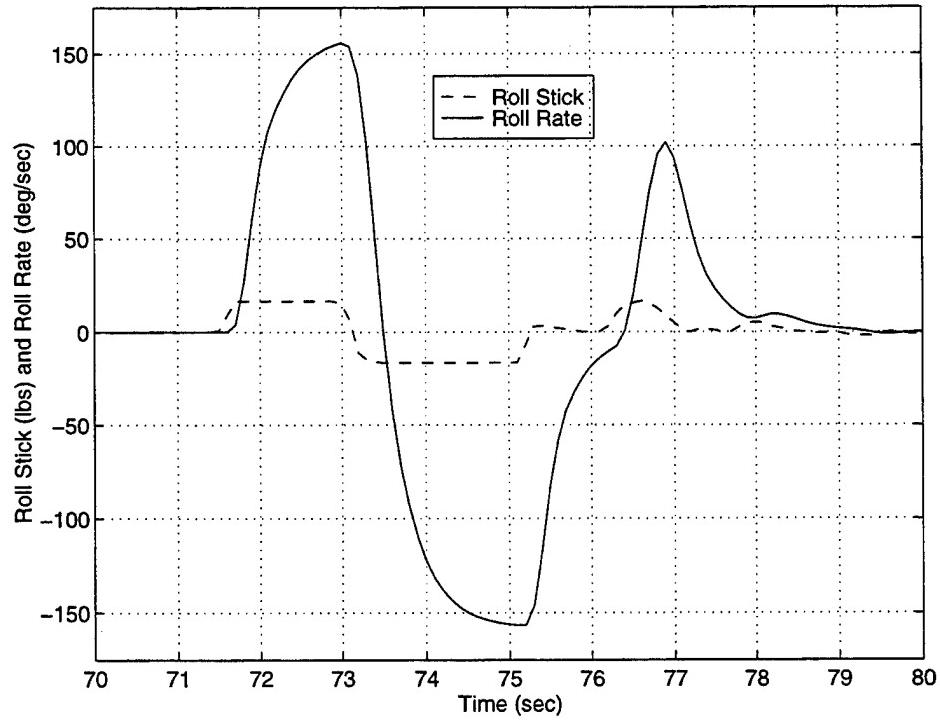


FIGURE 22. QFT Roll Response - High \bar{q} - Mach .9, 10,000 ft.

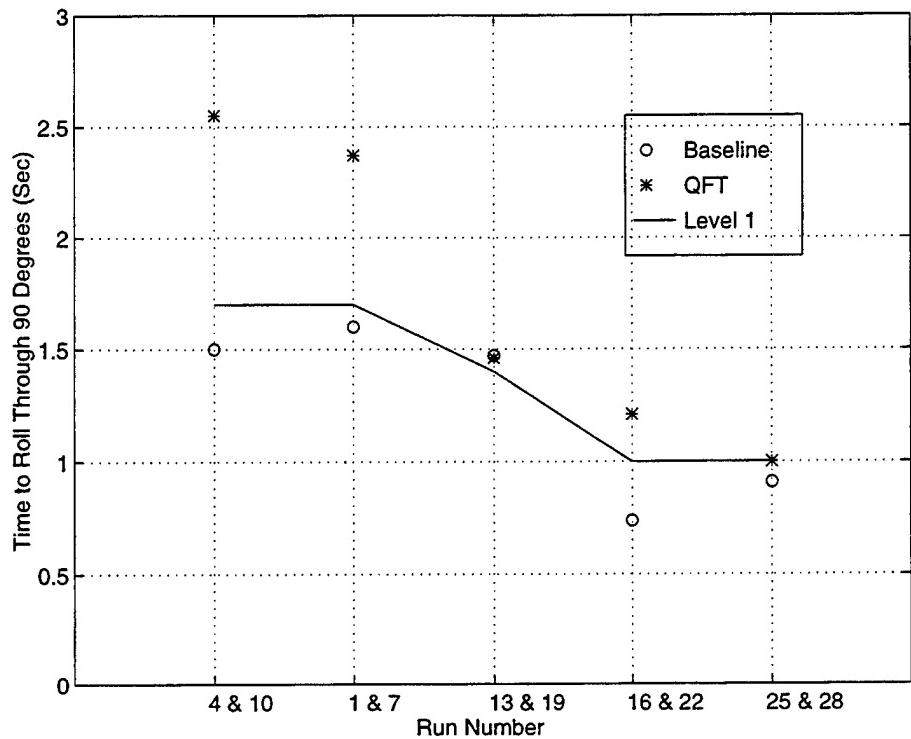


FIGURE 23. Time to Roll Through 90°

5.1.3 Yaw Response

One interesting and positive result of this test series was the aircraft response to pedal input. The baseline FCS induced a fast yaw rate followed by a large roll angle, actually inverting the aircraft at low dynamic pressures, in response to a full pedal command. The QFT system induced a smooth sideslip with very little roll. The pilot commented that this would be beneficial for strafing maneuvers. The yaw doublet response for the QFT FCS is shown in Figure 24. Comparison plots are shown in Appendix C.

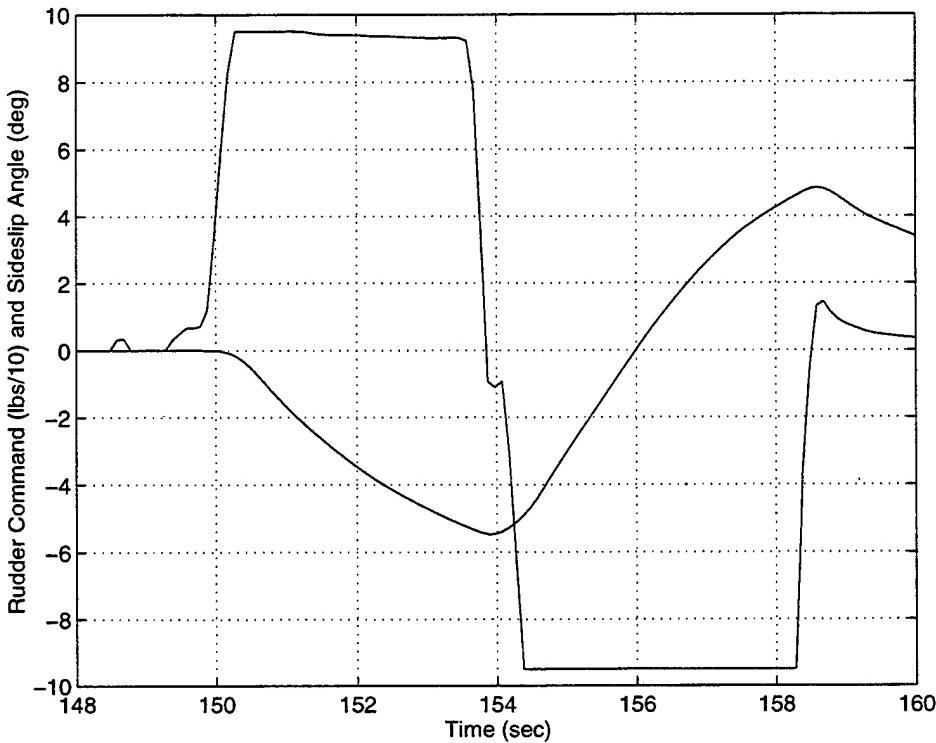


FIGURE 24. QFT FCS Yaw Response

5.1.4 Multichannel Response

Velocity vector rolls (loaded rolls) were performed with an objective of achieving angle-of-attack/sideslip angle (α/β) response similar to the baseline DFCS. Plots of the α/β response are shown in Appendix D. Responses were generally similar and neither system showed any tendency towards departure.

The pilot noted that the systems could achieve similar load factors during high \bar{q} maneuvers, but the baseline control system was able to achieve higher values of α at low \bar{q} . In addition, the QFT FCS had a tendency for the nose to fall more than the baseline system.

Due to the variability in the responses and the apparent lack of any trends, the only conclusion to be drawn is that the pilot should have been allowed to practise the maneuver before data was taken. It would also have been beneficial to run each simulation more than once in order to substantiate trend data.

5.2 Phase II, Positioning, Gross Acquisition and Fine Tracking

Phase II incorporated positioning, gross acquisition and fine tracking tasks. These tasks were used to provide an initial assessment of the handling qualities of the QFT based FCS compared to the baseline FCS. The intent was to note successes and identify deficiencies to be corrected in follow on research. The results were surprisingly positive. The QFT FCS performed nearly as well in most tasks and better than the baseline FCS in a few.

5.2.1 Pitch, Bank and Heading Angle Capture

Pitch, bank, and heading angle capture maneuvers were performed with the objectives of evaluating handling qualities and identifying maneuverability limitations and pilot-induced oscillation (PIO) tendencies. Comparison plots of these maneuvers are shown in Appendix E.

From straight and level flight, the pilot was told to pitch up to achieve and hold a 5° pitch angle above trim before gaining 100 feet in altitude. The pilot performed the task using his attitude direction indicator to judge the angles. The QFT FCS seemed to respond smoother and be easier to handle at low \bar{q} conditions as shown by Figure 25. The pilot rated the QFT FCS higher than the base line at low \bar{q} conditions, and both system were rated high at the high \bar{q} condition.

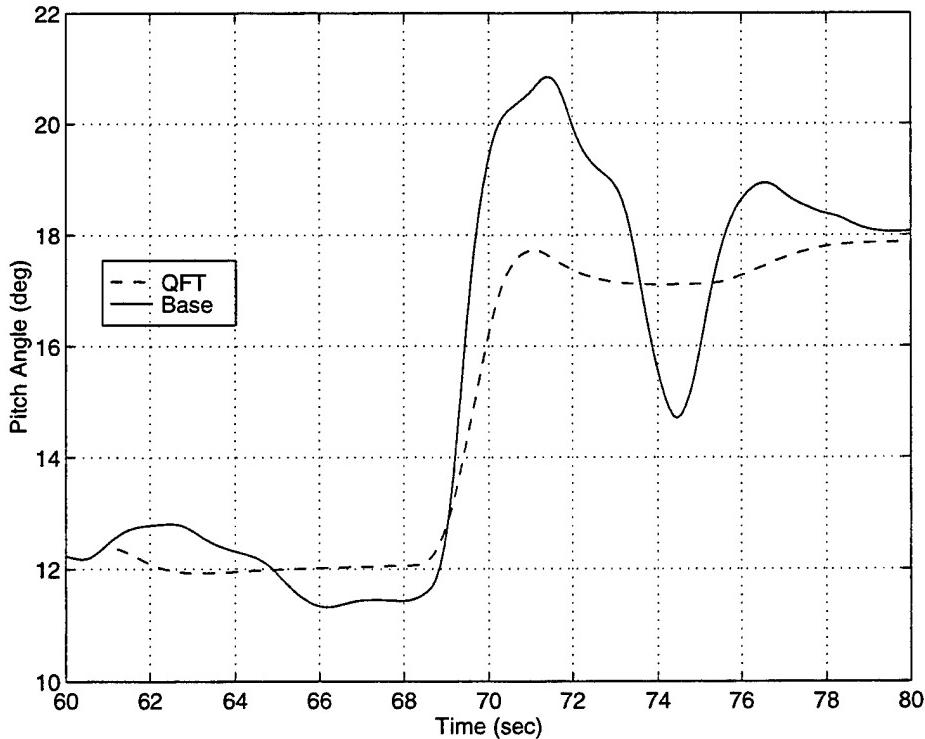


FIGURE 25. Pitch Angle Capture at Mach .3

Bank angle capture consisted of rolling to -45° bank angle, rolling to $+45^\circ$ bank angle and rolling back to level. The data showed responses that were similar at medium and high \bar{q} as seen in Figure 26. At low \bar{q} , the pilot rated the QFT FCS lower, largely because the QFT FCS allowed the nose to pitch down more. The pilot commented that there was a tendency of the QFT FCS to overshoot the bank angle, requiring a larger restoring input.

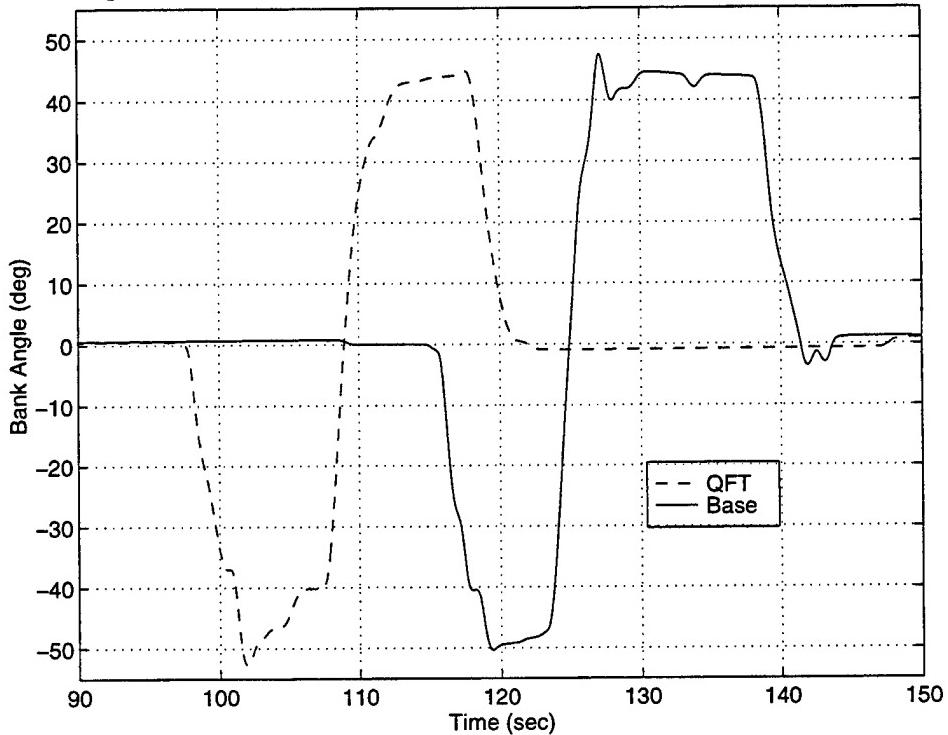


FIGURE 26. Bank Angle Capture at Mach .6

Heading angle capture involved turning at maximum turn rate and rolling out at a 90° heading change. This maneuver tested the predictability of the lateral directional channel. With the baseline FCS it was necessary to overshoot the target heading in order to be near it after the roll out making it unpredictable at some flight conditions. The QFT FCS does not require this large overshoot and was very predictable as shown in Figure 27.

This actually caused some difficulty in the simulation series as the pilot was used to flying the baseline controller and anticipated the need to overshoot. Unfortunately, the pilot conducted only one run of each test which made the QFT controller look unpredictable. In follow on simulations, the pilot should fly one control system through a practise session before conducting a series of data runs.

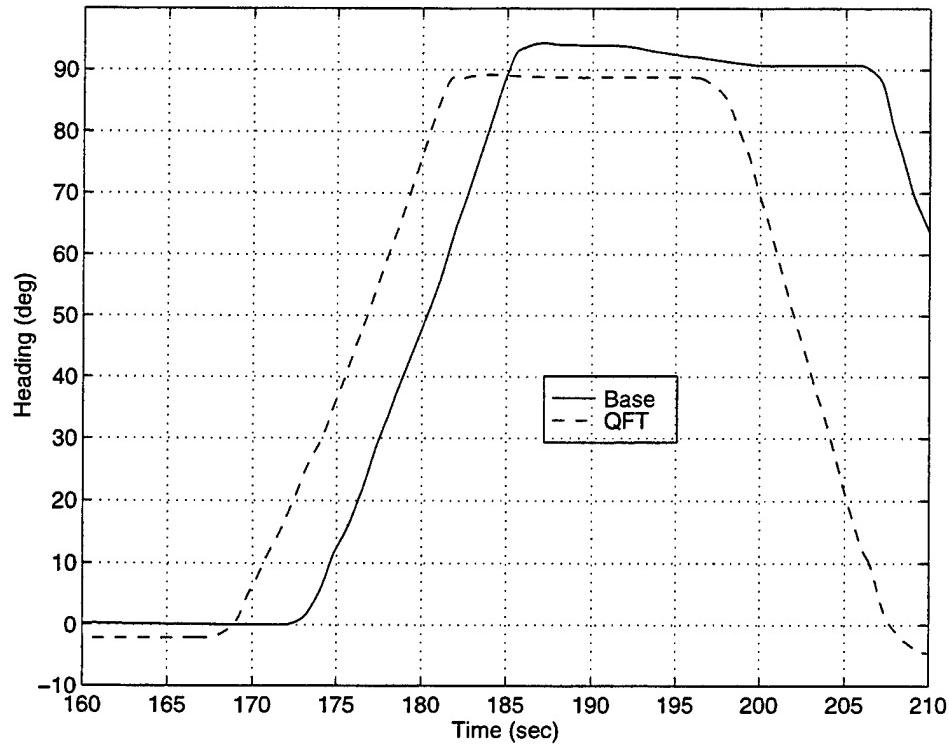


FIGURE 27. Heading Angle Capture, Mach .9

5.2.2 Multichannel Gross Acquisition

Multichannel gross acquisition maneuvers were performed to check handling qualities during elevated load factors and short-term response characteristics for aggressive pointing. Performed with a target aircraft, this maneuver tested the pilot's ability to turn onto and acquire a turning target.

The test and target aircraft began co-altitude at 10,000 feet, test aircraft in trail, with a 3,000 ft separation. At the start of the maneuver, the target aircraft rolled to a specified load factor and maintained altitude. The test aircraft delayed for 6 seconds then rolled toward the target to acquire the target for at least two seconds while maintaining the load factor. The target was considered acquired when the pilot tracked him within a 50 mil reticule.

Pilot ratings were recorded as Cooper-Harper ratings [6] shown in Table 1. This system uses a 10 point scale, 1 being highest, to rate aircraft controllability. Any rating from 1 to 3 is considered satisfactory without improvement. These ratings are very good for a flight control system in this first stage of development. The only deficiency noted was the tendency to oscillate like a dutch roll which was slightly worse for the QFT FCS than the baseline FCS.

Table 1: Cooper-Harper Ratings for Gross Acquisition Task

	Run A	Run B	Run C	Run D	Run E
\bar{q} (lb./sq. ft.)	92	367	367	825	825
QFT	2	2	2	2	1
Baseline	2	1	1	2	1

5.2.3 Longitudinal and Lateral HUD Tracking

Longitudinal and lateral Heads-Up Display (HUD) tracking were used to check feel and control sensitivity characteristics in a tight, closed-loop tracking task. This task was intended to expose pitch bobble or PIO tendencies. A sum of sine waves signal (Figure 28) was subtracted from the current pitch angle or bank angle of the aircraft and projected on the HUD. The pilot was tasked with nulling out this signal by maneuvering the aircraft. An example of the aircraft response during this test is shown in Figure 29.

This series of tests did not expose any problems with the QFT FCS. RMS measurements of the tracking error signal (Table 2) were within 5% of each other, suggesting no statistical difference between the systems for this task. The only notable pilot comment was that the QFT FCS seemed to respond quicker to longitudinal stick input than the baseline FCS.

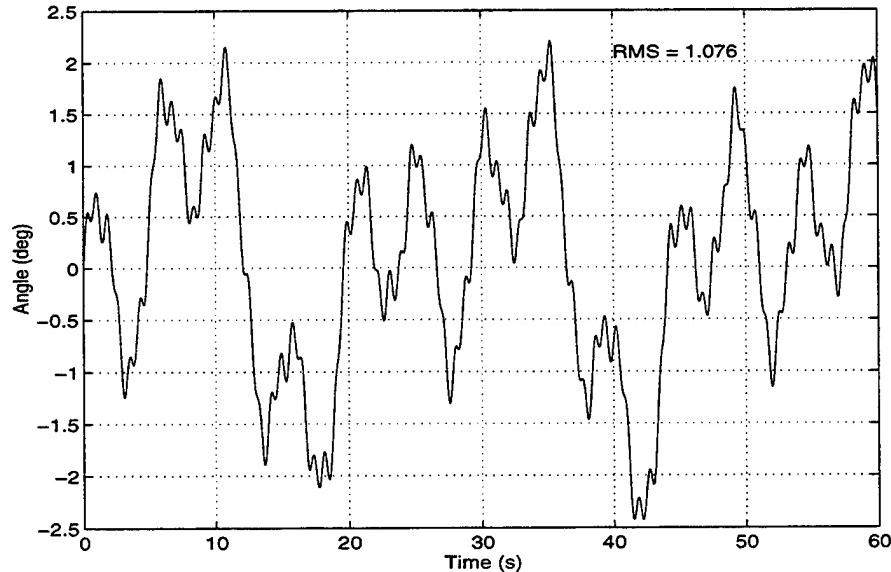


FIGURE 28. Pitch Attitude Disturbance Function

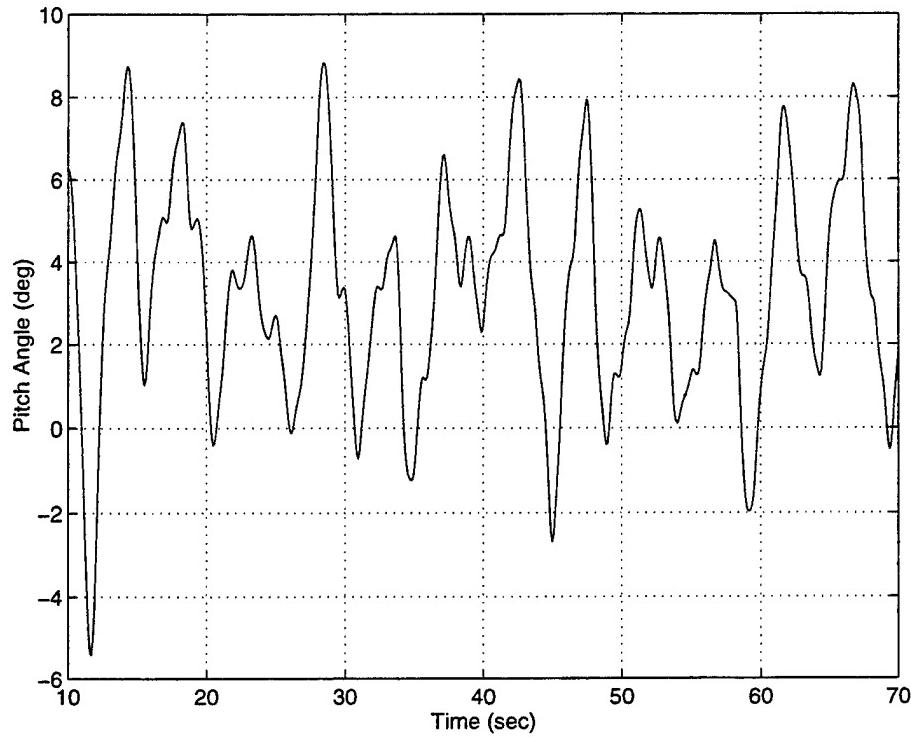


FIGURE 29. QFT Pitch Attitude Response at Mach .6

Table 2: HUD Tracking Response Metrics

	Mach .3	Mach .6	Mach .9
Baseline RMS Pitch Error	1.3333	1.3351	1.3089
QFT RMS Pitch Error	1.3328	1.3307	1.3293
Baseline RMS Roll Error	8.335	8.3697	8.3452
QFT RMS Roll Error	8.2779	8.3404	8.3364

5.2.4 Air-to-Air Fine Tracking

An air-to-air fine tracking task was performed to check the pilot's ability to gun track a target aircraft and expose short term longitudinal and lateral handling qualities deficiencies. After acquiring the target aircraft, the pilot was tasked to move his aim point to four different locations on the target aircraft, specifically, the nose, tail pipe, right wing tip, and left wing tip. These moves occurred at four second intervals and were designed to appear random, but were kept consistent for both systems.

The pilot rated the QFT FCS a 3, and the baseline FCS a 2 for this task. The pilot could track the target to within 10-15 mils with the baseline FCS and experienced only slight pitch oscillations. The pilot estimated tracking error over 20 mils with the QFT FCS and experienced a noticeable lateral oscillation similar to a dutch roll.

6.0 Conclusions

To reiterate, the objectives for simulating this control law design on a piloted simulator are as follows:

1. To test Phillips' design against a non-linear, 6DOF, simulation truth model emphasizing stability across entire design envelope.
2. To validate the achievement of the stated performance specifications.
3. To obtain initial handling/flying quality feedback for the QFT design which included handling/flying quality requirements a priori in the design.
4. To simulate flight scenarios not included in the design by Major Phillips, in order to investigate the degree of robustness inherent in a MIMO QFT design.
5. To investigate and document the performance of Phillips' command limiting scheme.

These simulations were intended to quantify the performance of a flight control system designed using the techniques of QFT. The primary intent was to demonstrate the viability of using QFT for flight control system design. Additionally, it was expected that piloted simulation would expose any deficiencies with the design so that the design procedure could be revised.

The QFT control laws provided level 1 handling qualities per the specifications in the pitch channel. It did not provide level 1 handling qualities in the lateral channel, but the response was better than one would expect for a first cut design accomplished in six months by a graduate student.

6.1 Deficiencies in the Design

The primary pitch channel deficiency is that the aircraft is not limited from producing large negative load factor. This should require a relatively simple adjustment to the current limiting scheme to make it asymmetric.

Although the pitch response met level 1 flying qualities, it may be desirable to allow more pitch rate overshoot to provide for slightly faster pitch response.

The primary roll channel deficiency is the slower than specified times to roll through 90°. This is an expected deficiency as the controller did not meet this specification in linear simulation. The time to roll specifications should be factored in to the roll channel performance specifications in order for a redesign to be successful. The solution to this problem may be as simple as modifying or even removing the roll channel prefilter.

There is a deficiency in the combined lateral directional channel response which showed up as a multichannel PIO in tasks 4 and 6. The design structure of the lateral channel should be reexamined to identify the cause of this behavior. Specifically, the yaw damper design should be reviewed to ensure that it is not creating more of a problem than it is solving.

6.2 Recommendations

The following recommendations for future work are submitted:

1. This design should be refined, and the deficiencies noted above corrected.
2. The results of this refined design should be simulated in an extensive, impartial handling qualities simulation program.
3. Future simulation programs should involve handling qualities specialists in order to develop a simulation test plan that fully explores the performance of the design.
4. A briefing to industry should be developed which would provide a means to transfer the QFT technology.

6.3 Summary

For flight control system design, QFT compares very favorably with current design methods. The excellent performance in these initial simulations demonstrated the viability of a QFT design approach in producing flight worthy aircraft control systems. It illustrated the benefits of designing flight control systems with a robust control design technique in contrast to the brute force approach of optimizing a flight control system for performance in expected configurations and then scheduling the gains.

Future work will take the results of these simulations and feed them back into a redesign. Since the entire subsonic flight envelope is addressed at once, redesign should be a very quick and simple process.

Appendix A

Detailed Test Scenario Requirements

I. Introduction

1. Objectives - To assess the stability, flying qualities, and robustness of the VISTA/F-16 aircraft with a robust digital flight control (DFCS) installed; with Block-40 performance as a baseline, assess viability of the DFCS designed using Quantitative Feedback Theory (QFT); validate results and design approach successfully reported in previous non real-time research.
2. Final Product - A summary report based on both quantitative data concerning the aircraft's dynamic performance and qualitative data describing the pilot's opinions of the aircraft flying qualities.

3. Mission Task Descriptions

A. - Phase I, Stability Tasks

Task 1 - Maximum Stick Doublet Response

Description: At multiple trimmed conditions (steady level flight) across the subsonic envelope, perform a series of doublets. Record data, verify nominal stability, observe secondary parameters, acclimate pilot, record pilot comments. Test points to include design points, off-design points, and variation with a/c configuration.

- a) Four second pitch doublet (2s aft / 2s fore) at max longitudinal stick, regain trim
- b) Four second roll doublet (2s right / 2s left) at max lateral stick, regain trim
- c) Ten second (5s right / 5s left) max pedal doublet, regain trim

Test Conditions: See table 1, test matrix

Desired Response: Second order transient response with no overshoot, minimal negative effect to secondary parameters (Mach,...) as compared to the Block-40 DFCS

Adequate Response Dynamic stability throughout maneuver

Task 2 - Velocity Vector (Loaded) Rolls

Description: From specified trim starting conditions, bank aircraft to 90 degrees and load aircraft (aft longitudinal stick) to generate angle of attack (AOA). Roll aircraft 180 degrees to achieve a 180 degree change in heading angle. Record data, verify stability in a challenging maneuver, record pilot comments. Recorded alpha and beta used to generate alpha/beta plots. Test points to include design points, off-design points, and variation with a/c configuration.

Test Conditions: See table 1, test matrix

Desired Response: Alpha/beta plots similar to those generated by Block-40 DFCS

Adequate Response: Dynamic stability throughout maneuver

B. - Phase II, Positioning/Gross Acquisition/Fine Tracking

Task 3 - Pitch, Bank, Heading Angle Capture

Pitch Description: Maintain straight-and-level flight at the reference altitude, with the pitch attitude constant within the specified tolerance, for at least 30 seconds before initiating the maneuver. Capture a pitch attitude 5 degrees above trim and maintain this attitude within the specified tolerance. The attitude must be captured before exceeding a change in altitude of 100 ft., the altitude ceiling.

Objectives:

- a) Check ability to pitch and capture attitude
- b) Identify maneuverability limitations and PIO tendencies

Test Conditions: See table 1, test matrix

Desired Response:

- a) +/- 1 degree pitch attitude
- b) No pitch attitude overshoots

Adequate Response:

- a) +/- 2 degrees pitch attitude
- b) No more than one pitch attitude overshoot

Bank Description: Maintain straight-and-level flight at the reference altitude, with the wings level within the specified tolerance, for at least 30 seconds before initiating the maneuver. Roll and capture a bank angle of 45 degrees within a maximum heading change of 10 degrees. Maintain this bank angle within the specified tolerance. Then capture and hold a bank angle of -45 degrees and maintain this bank angle within the specified tolerance. Finally, return to straight-and-level flight (0 degrees bank angle) at the original reference heading and maintain the bank angle within the specified tolerance for at least 30 seconds.

Objectives:

- a) Check ability to roll and capture a bank angle
- b) Identify maneuverability limitations and PIO tendencies

Test Conditions: See table 1, test matrix

Desired Response:

- a) +/- 2 degrees bank angle
- b) No bank angle overshoots

Adequate Performance:

- a) +/- 4 degrees bank angle
- b) No more than one bank angle overshoot

Heading Description: Initiate the maneuver in steady level flight. Perform a turn with either maximum turn rate or bank angle to a 90 degree heading change while maintaining altitude and Mach number. Thrust may be adjusted as required to assist in the performance of the maneuver. The maneuver is to be performed to the left and to the right.

Objectives:

- a) Check ability to accurately change heading
- b) Check ability to maintain turn rate with no objectionable oscillations

Test Conditions: See table 1, test matrix

Desired Performance:

- a) +/- 2 degrees deviation from final target heading
- b) +/- 10 kts deviation in altitude
- c) +/- 200 ft deviation in altitude
- d) Zero overshoots of target heading (beyond limit)

Adequate Performance:

- a) +/- 4 degrees deviation from final target heading
- b) +/- 25 kts deviation in speed
- c) +/- 400 ft deviation in altitude
- d) No more than one overshoot of target heading (beyond limit)

Task 4 - Multichannel Gross Acquisition

Gross Acquisition Description: Two aircraft are required for this maneuver. The test and target aircraft begin co-altitude, test aircraft in trail, with a 3,000 ft separation. At the start of the maneuver, the target aircraft rolls to a specified load factor at constant altitude. The test aircraft delays for 6 seconds then rolls toward the target to achieve the minimum load factor and acquire the target for at least two seconds while maintaining the load factor. Airspeed and turn rate should be varied to increase load factor from 2g to $0.9n_L(+)$.

Objectives:

- a) Check handling qualities during elevated load factors
- b) Check short-term response characteristics for aggressive pointing

Test Conditions: See table 1, test matrix

Desired Response:

- a) Maintain load factor within +/- 0.3g of minimum target load factor during the maneuver
- b) Acquire the target with no more than one overshoot and one undershoot of no more than 80 mils
- c) Acquire the target for at least 2 seconds within a 25 mil diameter pipper.
- d) No undesirable oscillations or pitch bobble.

Adequate Response:

- a) Maintain load factor within +/- 0.5g of minimum target load factor during the maneuver.
- b) Acquire the target with no more than two overshoots and one undershoot of no more than 80 mils.
- c) Acquire the target for at least 2 seconds within a 50 mil diameter pipper.
- d) Oscillations or pitch bobble shall not be objectionable.

Task 5 - Longitudinal, Lateral HUD Tracking

Longitudinal Tracking Description: Aggressively track a series of sine waves displayed on the HUD and attempt to keep pitch attitude error at zero. Perform the task for at least one minute.

Objectives:

- a) Check handling qualities in a tight, closed-loop tracking task
- b) Check feel system and control sensitivity characteristics
- c) Check for pitch bobble or PIO tendencies

Test Conditions: See table 1, test matrix

Desired Response:

- a) tracking within +/- 1 degrees

Adequate Response:

- a) tracking within +/- 2 degrees

Lateral Tracking Description: Aggressively track a series of sine waves displayed on the HUD and attempt to keep bank angle error at zero. Perform the task for at least one minute.

Objectives:

- a) Check handling qualities in a tight, closed-loop tracking task
- b) Check feel system and control sensitivity characteristics
- c) Check for roll ratchet or PIO tendencies

Test Conditions: See table 1, test matrix

Desired Response:

- a) tracking within +/- 7.5 degrees

Adequate Response:

- a) tracking within +/- 15 degrees

Task 6 - Air-to-Air Fine Tracking

Air-to-air Description: The target aircraft and the test aircraft trim at 250 KIAS +/- 5 KIAS and 15,000 ft +/- 100 ft. The tracking task starts with the test aircraft at a 2000 ft slant range position relative to the target, offset 10 degrees from the target aircraft's center line. At the evaluation pilot's "begin maneuver" call, the target initiates a 2g +/- 0.2g level turn. The evaluation pilot closes to 1500 ft +/- 300 ft slant range and begins fine tracking the target aircraft's tail pipe. The evaluation pilot calls "tracking" when stabilized. Test and target aircraft use power as required to maintain the test maneuver conditions. A test operator calls out a new aim point on the target aircraft in a predetermined, but apparently random order every 4 sec. Aim points include target tail pipe, wing tips, and canopy. The task is complete after 6 aim point changes. The evaluation pilot attempts to minimize tracking error using compensation as required to optimize performance. At the completion of the task, the evaluation pilot should judge an overall aim point tracking accuracy in mils.

Objectives:

- a) Check ability to gun track a target aircraft
- b) Expose short term longitudinal and lateral handling qualities deficiencies
- c) Check for longitudinal and lateral PIO tendencies

Test Conditions: See above

Desired Response:

- a) Track specific aim points on the target within 5 mils
- b) No aim point overshoots
- c) No undesired pitch or roll oscillations

Adequate Response:

- a) Track specific aim points on the target within 7 mils
- b) No more than one aim point overshoot
- c) No undesired pitch or roll oscillations

B. - Phase III, Off-design Robustness Check Tasks

Task 7 - Alternate CG Location Stability Check

Alternate CG Description: Re-run Task 5 tracking tasks with aircraft center of gravity moved fore/aft of the design condition, simulating fuel consumption. Vary also laterally, if possible, simulating stores or fuel imbalance.

Objectives:

- a) Demonstrate FCS stability robustness to variations in aircraft design truth model

Test Conditions: See table 1, test matrix

Desired Response: Same as Task 5

Adequate Response: Same as Task 5

Task 8 - Added Turbulence Stability Check

Turbulent Air-to-air Description: Re-run Task 6 with medium and high levels of turbulence added to the simulation.

Objectives:

- a) Demonstrate FCS disturbance rejection capabilities
- b) Same as Task 6

Test Conditions: Same as Task 6

Desired Response: Same as Task 6

Adequate Response: Same as Task 6

4. Mode of Operation - Normal

5. Constraints/Limitations - Based upon this document and similar simulation efforts, we estimate 40 hours of simulator (piloted) test time, not counting checkout, practice runs, etc.

II. Simulation Approach

1. Model Description

- a. Aircraft - FIGD's VISTA/F-16 simulation
- b. Weapons - Guns as primary weapon system for tracking tasks. Wing tip AIM-9s in standard configuration for a/c aerodynamics. (No weapons dynamics required as weapons will not be fired)
- c. Target - The target aircraft can be either pre-recorded or computer generated as decided upon mutually by FIGD and FIGS engineers.

2. Crew Station

- a. LAMARS standard VISTA/F-16 cockpit. Stick to be calibrated by FIGD. Sensitivity as dictated in the QFT DFCS design.
- b. HUD showing gun sight marker, flight path vector, speed, AOA, and pitch ladder. Artificial horizon required for lateral HUD tracking task. Bore sight suppression to be variable as a function of max g-level of target aircraft doing evasive maneuvers.

3. Visual Systems Requirements

- a. Sky/earth plus visual target, representative of rigid body aircraft motion in 6DOF. Sufficient aircraft graphic detail required for air-to-air tracking task.

4. Motion-base Requirements

- a. No motion required.

5. Audio Effects

- a. Standard FIGD VISTA/F-16 simulation audio effects apply.

6. Major System Interface

- a. None

III. Experiment Description Plan

1. Experiment Definition For each case identified in Table pilot will perform at most three repeats of the maneuver. The aircraft configurations to be used are defined below:
 - a. #1: Standard VISTA/F-16, wing tip AIM-9s, Block-40 DFCS (Standard Block-40)
 - b. #2: Standard VISTAF-16, wing tip AIM-9s, QFT DFCS (Standard QFT)
 - c. #3: Standard Block-40 w/2 370 gal external fuel tanks
 - d. #4: Standard QFT w/2 370 gal external fuel tanks
 - e. #5: Standard Block-40 w/300 gal center line fuel tank
 - f. #6: Standard QFT w/300 gal center line fuel tank
2. Test Pilots
 - a. Maj Scott Phillips
 - b. Familiarization time should be allotted for each of the task maneuvers identified in the Mission Task Description (Section I.3)
3. Performance Measures
 - a. Aircraft, pipper, target parameters, and pilot voice recordings. Also, pilot comments concerning flying/handling qualities recorded after each test run.
 - b. Data at every .1 sec on 8mm exabyte tapes, standard SUN Unix tar format. Data to include all standard aircraft parameters (AOA, sideslip, flight path angle, theta, phi, psi, angular rates and accelerations, throttle and stick commands, control surface deflections, rigid body velocities and accelerations, alt, etc...), and tracking info to include actual position of target aircraft and location of test aircraft bore sight (and test a/c). Units to be in degrees, deg/s, deg/s**2, etc.
 - c. Audio tapes of pilot comments
4. Simulation Validation/Verification Methods
 - a. Comparison with batch simulation results.
 - b. Pilot feedback
5. Reporting
 - a. All reporting will be done by FIGS w/FIGD as consultant.

Table A1: Test Matrix

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
1	T1	Mach .3, 10K ft, $\bar{q} = 92$	B40	Clean	Triple Doublet
2	T1	Mach .3, 10K ft, $\bar{q} = 92$	B40	Center Rig	Triple Doublet
3	T1	Mach .3, 10K ft, $\bar{q} = 92$	B40	Wing Tanks	Triple Doublet
4	T1	Mach .3, 12.5K ft	B40	Clean	Triple Doublet
5	T1	Mach .3, 12.5K ft	B40	Center Rig	Triple Doublet
6	T1	Mach .3, 12.5K ft	B40	Wing Tanks	Triple Doublet
7	T1	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Clean	Triple Doublet
8	T1	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Center Rig	Triple Doublet
9	T1	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Wing Tanks	Triple Doublet
10	T1	Mach .3, 12.5K ft	QFT	Clean	Triple Doublet
11	T1	Mach .3, 12.5K ft	QFT	Center Rig	Triple Doublet
12	T1	Mach .3, 12.5K ft	QFT	Wing Tanks	Triple Doublet
13	T1	Mach .7, 40K ft, $\bar{q} = 135$	B40	Clean	Triple Doublet
14	T1	Mach .7, 40K ft, $\bar{q} = 135$	B40	Center Rig	Triple Doublet
15	T1	Mach .7, 40K ft, $\bar{q} = 135$	B40	Wing Tanks	Triple Doublet
16	T1	Mach .9, 48K ft	B40	Clean	Triple Doublet
17	T1	Mach .9, 48K ft	B40	Center Rig	Triple Doublet
18	T1	Mach .9, 48K ft	B40	Wing Tanks	Triple Doublet
19	T1	Mach .7, 40K ft, $\bar{q} = 135$	QFT	Clean	Triple Doublet
20	T1	Mach .7, 40K ft, $\bar{q} = 135$	QFT	Center Rig	Triple Doublet
21	T1	Mach .7, 40K ft, $\bar{q} = 135$	QFT	Wing Tanks	Triple Doublet
22	T1	Mach .9, 48K ft	QFT	Clean	Triple Doublet
23	T1	Mach .9, 48K ft	QFT	Center Rig	Triple Doublet
24	T1	Mach .9, 48K ft	QFT	Wing Tanks	Triple Doublet
25	T1	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	Triple Doublet
26	T1	Mach .9, 10K ft, $\bar{q} = 825$	B40	Center Rig	Triple Doublet

Table A1: Test Matrix

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
27	T1	Mach .9, 10K ft, $\bar{q} = 825$	B40	Wing Tanks	Triple Doublet
28	T1	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	Triple Doublet
29	T1	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Center Rig	Triple Doublet
30	T1	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Wing Tanks	Triple Doublet
31	T2	Mach .3, 12.5Kft	B40	Clean	15, Max α
32	T2	Mach .3, 12.5K ft	B40	Center Rig	15, Max α
33	T2	Mach .3, 12.5K ft	B40	Wing Tanks	15, Max α
34	T2	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	3, 6, Max G
35	T2	Mach .9, 10K ft, $\bar{q} = 825$	B40	Center Rig	3, 6, Max G
36	T2	Mach .9, 10K ft, $\bar{q} = 825$	B40	Wing Tanks	3, 6, Max G
37	T2	Mach .3, 12.5K ft	QFT	Clean	15, Max α
38	T2	Mach .3, 12.5K ft	QFT	Center Rig	15, Max α
39	T2	Mach .3, 12.5K ft	QFT	Wing Tanks	15, Max α
40	T2	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	3, 6, Max G
41	T2	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Center Rig	3, 6, Max G
42	T2	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Wing Tanks	3, 6, Max G
43	T3	Mach .3, 10K ft, $\bar{q} = 92$	B40	Clean	Pitch, Bank, Heading
44	T3	Mach .6, 10K ft, $\bar{q} = 367$	B40	Clean	Pitch, Bank, Heading
45	T3	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	Pitch, Bank, Heading
46	T3	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Clean	Pitch, Bank, Heading
47	T3	Mach .6, 10K ft, $\bar{q} = 367$	QFT	Clean	Pitch, Bank, Heading
48	T3	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	Pitch, Bank, Heading
49	T4	Mach .3, 10K ft, $\bar{q} = 92$	B40	Clean	$n_L = 1.4$
50	T4	Mach .6, 10K ft, $\bar{q} = 367$	B40	Clean	$n_L = 2, 4$
51	T4	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	$n_L = 2, 5$
52	T4	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Clean	$n_L = 1.4$
53	T4	Mach .6, 10K ft, $\bar{q} = 367$	QFT	Clean	$n_L = 2, 4$

Table A1: Test Matrix

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
54	T4	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	$n_L = 2, 5$
55	T5	Mach .3, 10K ft, $\bar{q} = 92$	B40	Clean	longitudinal, lateral
56	T5	Mach .6, 10K ft, $\bar{q} = 367$	B40	Clean	longitudinal, lateral
57	T5	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	longitudinal, lateral
58	T5	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Clean	longitudinal, lateral
59	T5	Mach .6, 10K ft, $\bar{q} = 367$	QFT	Clean	longitudinal, lateral
60	T5	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	longitudinal, lateral
61	T6	As specified	B40	Clean	
62	T6	As specified	QFT	Clean	

Appendix B

Detailed Test Results and Pilot Comment Records

Date. 18 October 1995

Task 1, Case 1.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
1	T1	Mach .3, 10K ft, $\bar{q} = 92$	B40	Clean	Triple Doublet
2	T1	Mach .3, 10K ft, $\bar{q} = 92$	B40	Center Rig	Triple Doublet
3	T1	Mach .3, 10K ft, $\bar{q} = 92$	B40	Wing Tanks	Triple Doublet
4	T1	Mach .3, 12.5K ft	B40	Clean	Triple Doublet
5	T1	Mach .3, 12.5K ft	B40	Center Rig	Triple Doublet
6	T1	Mach .3, 12.5K ft	B40	Wing Tanks	Triple Doublet

Pilot Comments.

No significant performance deviation with stores.

Typical Block 40 flight control system.

Rudder is not a primary input, and this shows. (Recorder comment: It is apparently unnatural for a pilot to perform a yaw doublet.)

Initial Response	Pitch	Medium
	Roll	Fast
	Yaw	Slow
Predictability	Excellent	
Final Response	Pitch	Medium
	Roll	Medium
	Yaw	Medium
Stability	Good	

Date. 18 October 1995

Task 1, Case 2.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
7	T1	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Clean	Triple Doublet
8	T1	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Center Rig	Triple Doublet
9	T1	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Wing Tanks	Triple Doublet
10	T1	Mach .3, 12.5K ft	QFT	Clean	Triple Doublet
11	T1	Mach .3, 12.5K ft	QFT	Center Rig	Triple Doublet
12	T1	Mach .3, 12.5K ft	QFT	Wing Tanks	Triple Doublet

Pilot Comments.

(Recorder comment: There is no roll coordination)

Initial Response	Pitch	Medium (Positive similar/ down slower)
	Roll	Medium to Fast
	Yaw	Slow
Predictability		Excellent
Final Response	Pitch	Medium
	Roll	Medium
	Yaw	Slow
Stability	Pitch	Good
	Roll	Good
	Yaw	Very Good

No significant difference in coordination

Both Block 40 and QFT easy to recover to original positions

Date. 18 October 1995

Task 1, Case 3.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
13	T1	Mach .7, 40K ft, $\bar{q} = 135$	B40	Clean	Triple Doublet
14	T1	Mach .7, 40K ft, $\bar{q} = 135$	B40	Center Rig	Triple Doublet
15	T1	Mach .7, 40K ft, $\bar{q} = 135$	B40	Wing Tanks	Triple Doublet
16	T1	Mach .9, 48K ft	B40	Clean	Triple Doublet
17	T1	Mach .9, 48K ft	B40	Center Rig	Triple Doublet
18	T1	Mach .9, 48K ft	B40	Wing Tanks	Triple Doublet

Pilot Comments.

At high \bar{q} conditions - giving a bit more throttle before maneuver to maintain q throughout maneuver

(Recorder: moved off nominal point from Mach .7, 48K to Mach .9, 48K because simulation had difficulty initializing runs 16-18)

Initial Response	Pitch	Medium
	Roll	Fast
	Yaw	Medium
Predictability	Pitch	Satisfactory
	Roll	Excellent
	Yaw	Excellent
Final Response	Pitch	Medium
	Roll	Fast
	Yaw	Medium
Stability	Good	

No performance deviation with stores except maybe with center tank on pitch maneuver

Less dip on the nose in roll maneuver over low q condition

Purer yaw initially before adverse roll began over low q condition

No variation in on/off design point (versus low \bar{q})

No significant variation in stores (versus low \bar{q})

No significant difference in coordination (versus low \bar{q})

Date. 18 October 1995

Task 1, Case 4.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
19	T1	Mach .7, 40K ft, $\bar{q} = 135$	QFT	Clean	Triple Doublet
20	T1	Mach .7, 40K ft, $\bar{q} = 135$	QFT	Center Rig	Triple Doublet
21	T1	Mach .7, 40K ft, $\bar{q} = 135$	QFT	Wing Tanks	Triple Doublet
22	T1	Mach .9, 48K ft	QFT	Clean	Triple Doublet
23	T1	Mach .9, 48K ft	QFT	Center Rig	Triple Doublet
24	T1	Mach .9, 48K ft	QFT	Wing Tanks	Triple Doublet

Pilot Comments.

Initial Response	Pitch	Medium
	Roll	Fast
	Yaw	Slow
Predictability	Pitch	Excellent (Better than Block 40)
	Roll	Excellent
	Yaw	Excellent
Final Response	Pitch	Medium
	Roll	Fast
	Yaw	Slow
Stability	Pitch	Good
	Roll	Good
	Yaw	Very Good

Variation in stores noticeable in pitch channel only

Roll response closer to block 40

Pitch similar for both

No variation between on/off nominal

Easy enough to bring both FCS to trim condition between doublets

Date. 18 October 1995

Task 1, Case 3 repeated.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
16	T1	Mach .9, 48K ft	B40	Clean	Triple Doublet
17	T1	Mach .9, 48K ft	B40	Center Rig	Triple Doublet
18	T1	Mach .9, 48K ft	B40	Wing Tanks	Triple Doublet

Pilot Comments.

Initial Response	Pitch	Medium
	Roll	Fast
	Yaw	Medium
Predictability	Pitch	Satisfactory
	Roll	Satisfactory
	Yaw	Satisfactory
Final Response	Pitch	Medium
	Roll	Fast
	Yaw	Medium
Stability	Good	

(Recorder comment: In 2 tank configuration there is not as much roll on pitch down)

Date. 18 October 1995

Task 1, Case 5.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
25	T1	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	Triple Doublet
26	T1	Mach .9, 10K ft, $\bar{q} = 825$	B40	Center Rig	Triple Doublet
27	T1	Mach .9, 10K ft, $\bar{q} = 825$	B40	Wing Tanks	Triple Doublet

Pilot Comments.

Initial Response	Pitch	Medium (Slow to pitch down)
	Roll	Fast
	Yaw	Medium
Predictability	Pitch	Excellent
	Roll	Excellent
	Yaw	Excellent
Final Response	Pitch	Medium (Slow down)
	Roll	Fast
	Yaw	Medium
Stability	Good	
		Good response pitching up but not so good pitching down
		Yaw input - not much roll compared to low q conditions
		Much slower roll
		No significant difference between configurations

Date. 18 October 1995

Task 1, Case 5.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
28	T1	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	Triple Doublet
29	T1	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Center Rig	Triple Doublet
30	T1	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Wing Tanks	Triple Doublet

Pilot Comments.

Initial Response **Pitch** **Medium (Good down)**

(Recorder note: Normal is -3g (-5° AOA) now seeing -6 g (-14° AOA))

Roll Fast

Yaw **Slow**

Predictability Pitch Excellent

Roll Excellent

Yaw **Excellent**

Final Response Pitch Medium

Roll Fast

Yaw **Slow**

Stability **Pitch** **Good**

Roll Good

Yaw **Very**

No difference in configuration

Pitch response nose down m

Roll similar to block 40 - well dam

Date. 20 October 95

Task 2, Case 3.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
37	T2	Mach .3, 12.5K ft	QFT	Clean	15°, Max α
38	T2	Mach .3, 12.5K ft	QFT	Center Rig	15°, Max α
39	T2	Mach .3, 12.5K ft	QFT	Wing Tanks	15°, Max α

Pilot Comments.

Fought to hold 90° right with clean configuration

Not as bad with center tank

Initial Response Slow

Final Response Medium

Stability Stable

Predictability Good

Pilot workload 15° Low

Max High

Date. 20 October 95

Task 2, Case 4.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
40	T2	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	3, 6, Max G
41	T2	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Center Rig	3, 6, Max G
42	T2	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Wing Tanks	3, 6, Max G

Pilot Comments.

Roll response better faster initially and easier to control at the end

Initial Response Fast

Final Response Fast

Stability Stable

Predictability Very Predictable

Pilot workload Low at all three conditions

No difference between configurations

Date. 20 October 95

Task 2, Case 1.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
31	T2	Mach .3, 12.5Kft	B40	Clean	15°, Max α
32	T2	Mach .3, 12.5K ft	B40	Center Rig	15°, Max α
33	T2	Mach .3, 12.5K ft	B40	Wing Tanks	15°, Max α

Pilot Comments.

Max AOA - QFT response is quicker

More AOA on max AOA pull

Easier to capture 90° at the end

Initial Response 15° Medium

 Max Slow

Final Response 15° Medium

 Max Slow

Stability Medium

Predictability Very predictable

Pilot workload 15° Comparable to QFT

 Max Lower than QFT

Date. 20 October 95

Task 2, Case 2.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
34	T2	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	3, 6, Max G
35	T2	Mach .9, 10K ft, $\bar{q} = 825$	B40	Center Rig	3, 6, Max G
36	T2	Mach .9, 10K ft, $\bar{q} = 825$	B40	Wing Tanks	3, 6, Max G

Pilot Comments.

Initial Response 3g Fast

Final Response 3g Fast

Stability Good

Predictability Very predictable

Pilot workload Low

In comparison to QFT - a little lower workload

Difference in stick force

Lower pitch stick to get same AOA with block 40

Could not tell difference in difficulty to achieve AOA

Roll rates comparable

High AOA Block 40 slower than Max AOA QFT

Date. 29 April 97

Task 1, Case 1.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
1	T1	Mach .3, 10K ft, $\bar{q} = 92$	B40	Clean	Triple Doublet

Pilot Comments.

Initial Response	Pitch	Medium
	Roll	Fast
	Yaw	Medium
Predictability	Pitch	Very Predictable (Excellent)
	Roll	Satisfactory
	Yaw	Satisfactory
Final Response	Pitch	Medium
	Roll	Fast
	Yaw	Slow
Stability	Satisfactory	

Recorder note: The aircraft rolled over 100° during the yaw doublet

Date. 29 April 97

Task 1, Case 3.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
13	T1	Mach .7, 40K ft, $\bar{q} = 135$	B40	Clean	Triple Doublet

Pilot Comments.

Initial Response	Pitch	Medium
	Roll	Fast
	Yaw	Medium
Predictability	Pitch	Satisfactory
	Roll	Satisfactory
	Yaw	Satisfactory
Final Response	Pitch	Medium
	Roll	Fast
	Yaw	Slow
Stability	Satisfactory	

Recorder note: The aircraft rolled approximately 90° during the yaw doublet

Date. 29 April 97

Task 1, Case 5.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
25	T1	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	Triple Doublet

Pilot Comments.

Initial Response	Pitch	Fast
	Roll	Fast
	Yaw	Fast
Predictability	Pitch	Excellent
	Roll	Excellent
	Yaw	Excellent
Final Response	Pitch	Fast
	Roll	Fast
	Yaw	Slow
Stability	Very Stable (Excellent)	

Recorder note: The aircraft rolled approximately 20° during the yaw doublet

Date. 29 April 97

Task 3, Case 1.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
43	T3	Mach .3, 10K ft, $\bar{q} = 92$	B40	Clean	Pitch, Bank, Heading
44	T3	Mach .6, 10K ft, $\bar{q} = 367$	B40	Clean	Pitch, Bank, Heading
45	T3	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	Pitch, Bank, Heading

Pilot Comments.

Run 43	Pitch	Bank	Heading
Cooper-Harper Rating	2	2	2
Response	Fast	Fast	Fast
Predictability	Excellent	Satisfactory	Satisfactory
Stability	Excellent	Satisfactory	Satisfactory
PIO Tendency	Slight*	Very Slight	None
Workload	Medium	Medium	Medium
Run 44			
Cooper-Harper Rating	1	2	1
Response	Fast	Fast	Fast
Predictability	Excellent	Satisfactory	Excellent
Stability	Excellent	Satisfactory	Excellent
PIO Tendency	None	Very Slight	None
Workload	Light	Light	Light
Run 45			
Cooper-Harper Rating	1	1	1
Response	Fast	Fast	Fast
Predictability	Excellent	Excellent	Excellent
Stability	Excellent	Excellent	Excellent
PIO Tendency	None	None	None
Workload	Light	Light	Light

Used heads down displays for pitch angle capture.

* Slight PIO tendency = tendency to overshoot and hard to capture angle exactly

Date. 29 April 97

Task 4, Case 1.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
49	T4	Mach .3, 10K ft, $\bar{q} = 92$	B40	Clean	$n_L = 2$
50	T4	Mach .6, 10K ft, $\bar{q} = 367$	B40	Clean	$n_L = 2, 4$
51	T4	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	$n_L = 2, 5$

Pilot Comments.

Run 49		$n_L = 2$	
Cooper-Harper Rating		2	
Response		Fast	
Predictability		Satisfactory	
Stability		Satisfactory	
PIO Tendency		None	
Workload		Light	
Run 50		$n_L = 2$	$n_L = 4$
Cooper-Harper Rating		1	1
Response		Fast	Fast
Predictability		Excellent	Excellent
Stability		Excellent	Excellent
PIO Tendency		None	None
Workload		Light	Light
Run 51		$n_L = 2$	$n_L = 5$
Cooper-Harper Rating		1	1
Response		Fast	Fast
Predictability		Excellent	Excellent
Stability		Excellent	Excellent
PIO Tendency		None	None
Workload		Light	Light

Date. 29 April 97

Task 4, Case 2.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
52	T4	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Clean	$n_L = 2$
53	T4	Mach .6, 10K ft, $\bar{q} = 367$	QFT	Clean	$n_L = 2, 4$
54	T4	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	$n_L = 2, 5$

Pilot Comments.

Run 52		$n_L = 2$	
Cooper-Harper Rating		2	
Response		Fast	
Predictability		Satisfactory	
Stability		Satisfactory	
PIO Tendency		None	
Workload		Light	
Run 53		$n_L = 2$	$n_L = 4$
Cooper-Harper Rating		1	1
Response		Fast	Fast
Predictability		Excellent	Excellent
Stability		Excellent	Excellent
PIO Tendency		None	None
Workload		Light	Light
Run 54		$n_L = 2$	$n_L = 5$
Cooper-Harper Rating		1	1
Response		Fast	Fast
Predictability		Excellent	Excellent
Stability		Excellent	Excellent
PIO Tendency		None	None
Workload		Light	Light

Date. 29 April 97

Task 1, Case 1.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
7	T1	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Clean	Triple Doublet

Pilot Comments.

Initial Response	Pitch	Medium
	Roll	Medium
	Yaw	Medium
Predictability	Pitch	Excellent (Very Predictable)
	Roll	Excellent
	Yaw	Excellent
Final Response	Pitch	Medium
	Roll	Medium
	Yaw	Slow
Stability	Excellent	

Recorder note: The aircraft rolled less than 5° during the yaw doublet

Date. 29 April 97

Task 1, Case 3.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
13	T1	Mach .7, 40K ft, $\bar{q} = 135$	QFT	Clean	Triple Doublet

Pilot Comments.

Initial Response	Pitch	Fast
	Roll	Fast
	Yaw	Medium
Predictability	Pitch	Excellent
	Roll	Excellent
	Yaw	Excellent
Final Response	Pitch	Fast
	Roll	Fast
	Yaw	Medium
Stability	Excellent	

Pitch and roll are comparable to the B40. QFT is faster pitching down as there is no limiting.

Roll induced during the pitch was inadvertent pilot input

There is no roll induced by the yaw

For the B40 there is an initial yaw which stops, the QFT has a constantly increasing yaw response

Recorder note: The aircraft rolled about 1° during the yaw doublet

Date. 29 April 97

Task 1, Case 5.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
28	T1	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	Triple Doublet

Pilot Comments.

Initial Response	Pitch	Fast
	Roll	Fast
	Yaw	Medium
Predictability	Pitch	Excellent
	Roll	Excellent
	Yaw	Excellent
Final Response	Pitch	Fast
	Roll	Fast
	Yaw	Medium
Stability	Satisfactory	

The QFT FCS is slower than the B40 but more controllable for tracking tasks

Recorder note: No noticeable roll

Date. 29 April 97

Task 1, Case 2.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
10	T1	Mach .3, 12.5K ft	QFT	Clean	Triple Doublet

Pilot Comments.

Initial Response	Pitch	Medium
	Roll	Medium
	Yaw	Slow
Predictability	Excellent	
Final Response	Pitch	Medium
	Roll	Medium
	Yaw	Slow
Stability	Pitch	Excellent
	Roll	Excellent
	Yaw	Excellent

Slower response as it is a lower \bar{q}

More induced roll on pedal doublet, but on release of pedals returned to straight and level flight.

Date. 29 April 97

Task 1, Case 4.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
22	T1	Mach .9, 48K ft	QFT	Clean	Triple Doublet

Pilot Comments.

Initial Response	Pitch	Medium
	Roll	Fast
	Yaw	Slow
Predictability	Pitch	Excellent
	Roll	Excellent
	Yaw	Excellent
Final Response	Pitch	Medium
	Roll	Fast
	Yaw	Slow
Stability	Pitch	Excellent
	Roll	Excellent
	Yaw	Excellent

Date. 29 April 97

Task 3, Case 2.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
46	T3	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Clean	Pitch, Bank, Heading
47	T3	Mach .6, 10K ft, $\bar{q} = 367$	QFT	Clean	Pitch, Bank, Heading
48	T3	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	Pitch, Bank, Heading

Pilot Comments.

Run 46	Pitch	Bank	Heading
Cooper-Harper Rating	1	3*	2
Response	Fast	Fast	Fast
Predictability	Excellent	Satisfactory	Satisfactory
Stability	Excellent	Excellent	Satisfactory
PIO Tendency	None	Slight	None
Workload	Light	Medium	Medium

Run 47			
Cooper-Harper Rating	1	1	1
Response	Fast	Fast	Fast
Predictability	Excellent	Excellent	Excellent**
Stability	Excellent	Excellent	Excellent
PIO Tendency	None	None	None
Workload	Light	Light	Light

Run 48			
Cooper-Harper Rating	1	1	1
Response	Fast	Fast	Fast
Predictability	Excellent	Excellent	Excellent
Stability	Excellent	Excellent	Excellent
PIO Tendency	None	None	None
Workload	Light	Light	Light

Used instruments (heads down) for pitch angle capture and combination of HUD and instruments for heading angle captures

* Nose drops more than B40 during bank angle capture and more PIO tendency

** Anticipated need to overshoot for roll out, didn't need to.

Date. 1 May 97

Task 2, Case 1.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
31	T2	Mach .3, 12.5Kft	B40	Clean	15°, Max α

Pilot Comments.

	15°	Max α
Initial Response	Fast	Medium
Final Response	Fast	Medium
Stability	Excellent	Excellent
Predictability	Excellent	Excellent
Pilot workload	Light	Light

Task 2, Case 2.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
34	T2	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	3, 6, Max G

Pilot Comments.

	3g	6g	Max g
Initial Response	Fast	Fast	Fast
Final Response	Fast	Fast	Fast
Stability	Excellent	Excellent	Excellent
Predictability	Excellent	Excellent	Excellent
Pilot workload	Light	Light	Light

Date. 1 May 97

Task 2, Case 4.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
40	T2	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	3, 6, Max G

Pilot Comments.

	3g	6g	Max g
Initial Response	Fast	Fast	Fast
Final Response	Fast	Fast	Fast
Stability	Excellent	Excellent	Excellent
Predictability	Excellent	Excellent	Excellent
Pilot workload	Light	Light	Light

Can't tell much of a difference from the B40

Task 2, Case 3.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
37	T2	Mach .3, 12.5K ft	QFT	Clean	15°, Max α

Pilot Comments.

	15°	Max α
Initial Response	Medium	Medium
Final Response	Medium	Medium
Stability	Excellent	Excellent
Predictability	Excellent	Excellent
Pilot workload	Light	Light

More difficult to stop bank angle - needs more damping from the pilot

Nose has a tendency to fall - perhaps due to "design being done not in stability axis"

Recorder note: lots of yaw oscillations

Date. 1 May 97

Task 4, Case 2.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
52	T4	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Clean	$n_L = 1.4$
53	T4	Mach .6, 10K ft, $\bar{q} = 367$	QFT	Clean	$n_L = 2, 4$
54	T4	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	$n_L = 2, 5$

Pilot Comments.

Run 52	$n_L = 1.4$	
Cooper-Harper Rating	2	
Response	Fast	
Predictability	Satisfactory	
Stability	Satisfactory	
PIO Tendency	Slight *	
Workload	Light	
Run 53	$n_L = 2$	$n_L = 4$
Cooper-Harper Rating	2	2
Response	Fast	Fast
Predictability	Excellent	Excellent
Stability	Excellent	Excellent
PIO Tendency	Very Slight **	Very Slight
Workload	Light	Light
Run 54	$n_L = 2$	$n_L = 5$
Cooper-Harper Rating	2	1
Response	Fast	Fast
Predictability	Excellent	Excellent
Stability	Excellent	Excellent
PIO Tendency	Slight ***	None
Workload	Light	Light

* PIO in roll channel

** Multichannel PIO

*** PIO in pitch channel

Date. 1 May 97

Task 4, Case 1.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
49	T4	Mach .3, 10K ft, $\bar{q} = 92$	B40	Clean	$n_L = 1.4$
50	T4	Mach .6, 10K ft, $\bar{q} = 367$	B40	Clean	$n_L = 2, 4$
51	T4	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	$n_L = 2, 5$

Pilot Comments.

Run 49		$n_L = 1.4$	
Cooper-Harper Rating		2	
Response		Medium	
Predictability		Excellent	
Stability		Excellent	
PIO Tendency		Slight *	
Workload		Light	
Run 50		$n_L = 2$	$n_L = 4$
Cooper-Harper Rating		1	1
Response		Fast	Fast
Predictability		Excellent	Excellent
Stability		Excellent	Excellent
PIO Tendency		None	None
Workload		Light	Light
Run 51		$n_L = 2$	$n_L = 5$
Cooper-Harper Rating		2	1
Response		Fast	Fast
Predictability		Excellent	Excellent
Stability		Excellent	Excellent
PIO Tendency		Slight	None
Workload		Light	Light

* PIO in roll channel

On run 50 QFT had more of a PIO tendency

Recorder note: 51 took longer to acquire

High \bar{q} 2 g is the hardest task because the target is turning too slow -- comparable between two FCS, 5g task comparable with no significant differences

Date. 1 May 97

Task 6, Case 1, QFT.

Pilot comments.

	Left Turn	Right Turn
Tracking accuracy:	20 mils	20 mils
Handling Quality	3	3
Predictability	Satisfactory	Satisfactory
PIO tendency	Medium *	Medium *

* As you roll you get some yaw (left to right) oscillation

Task 6, Case 2, B40.

Pilot comments.

	Left Turn	Right Turn
Tracking accuracy:	10 mils	15 mils
Handling Quality	2	2
Predictability	Excellent	Excellent
PIO tendency	Slight **	Slight **

** PIO tendency in pitch

Date. 1 May 97

Task 5, Case 2.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
58	T5	Mach .3, 10K ft, $\bar{q} = 92$	QFT	Clean	longitudinal, lateral
59	T5	Mach .6, 10K ft, $\bar{q} = 367$	QFT	Clean	longitudinal, lateral
60	T5	Mach .9, 10K ft, $\bar{q} = 825$	QFT	Clean	longitudinal, lateral

Pilot Comments.

	Run 58		Run 59		Run 60	
	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral
Response	Fast	Medium	Fast	Fast	Fast	Fast
Stability	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Workload	Heavy	Heavy	Heavy	Heavy	Heavy	Heavy

No PIO tendencies

Task is demanding \Rightarrow heavy workload

Task 5, Case 1.

Run	Task	Flight Condition	FCS	Configuration	Maneuver Notes
55	T5	Mach .3, 10K ft, $\bar{q} = 92$	B40	Clean	longitudinal, lateral
56	T5	Mach .6, 10K ft, $\bar{q} = 367$	B40	Clean	longitudinal, lateral
57	T5	Mach .9, 10K ft, $\bar{q} = 825$	B40	Clean	longitudinal, lateral

Pilot Comments.

	Run 55		Run 56		Run 57	
	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral
Response	Fast	Medium	Fast	Fast	Fast	Fast
Stability	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Workload	Heavy	Heavy	Heavy	Heavy	Heavy	Heavy

Run 55 - More transient delay between input and response in B40 pitch channel

Similar response in roll

Run 56 and 57 - No perceived difference between B40 and QFT responses

Appendix C

Doublet Comparison Plots

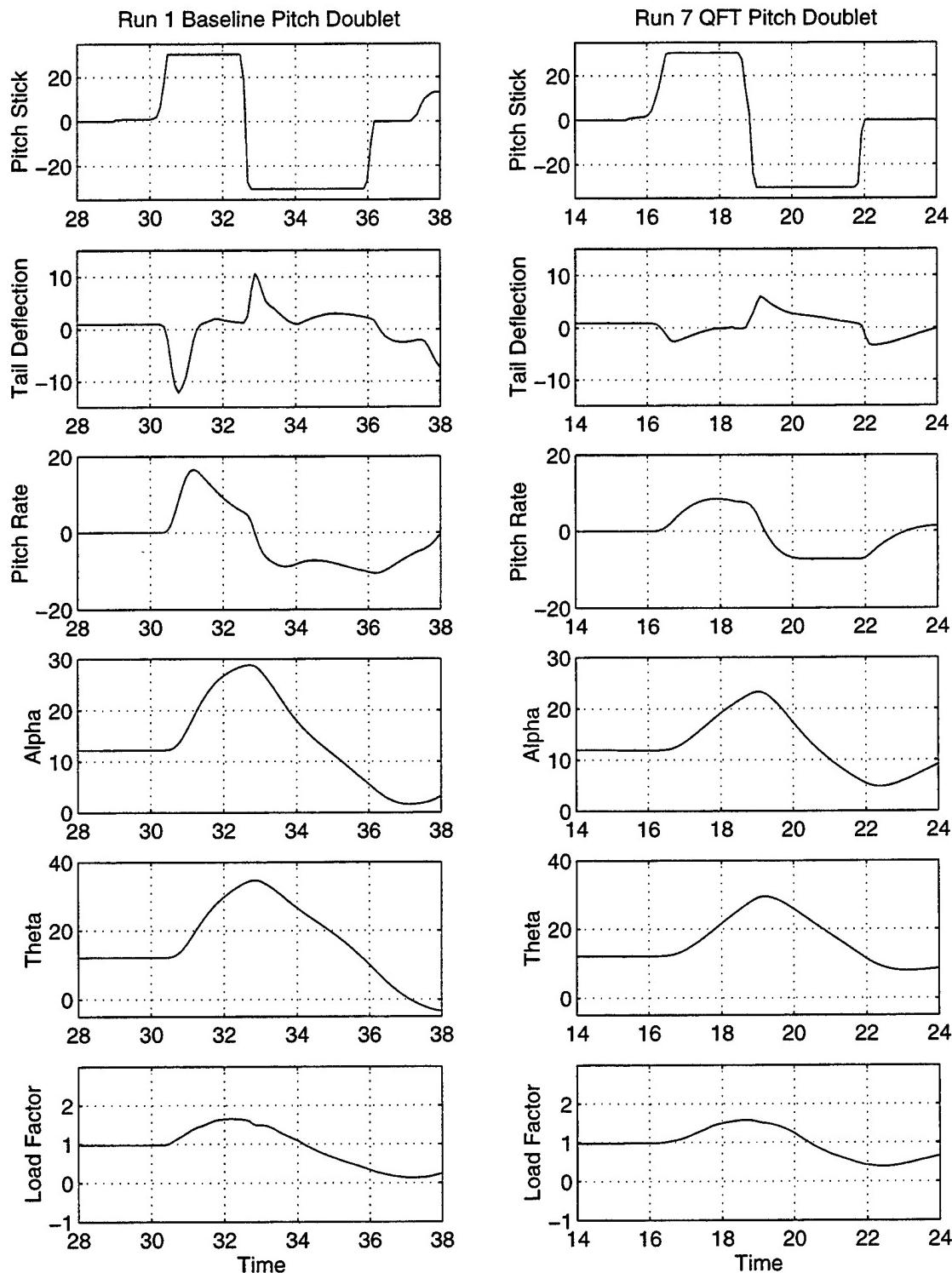


FIGURE C1. Pitch Doublet at Mach .3, 10,000 ft.

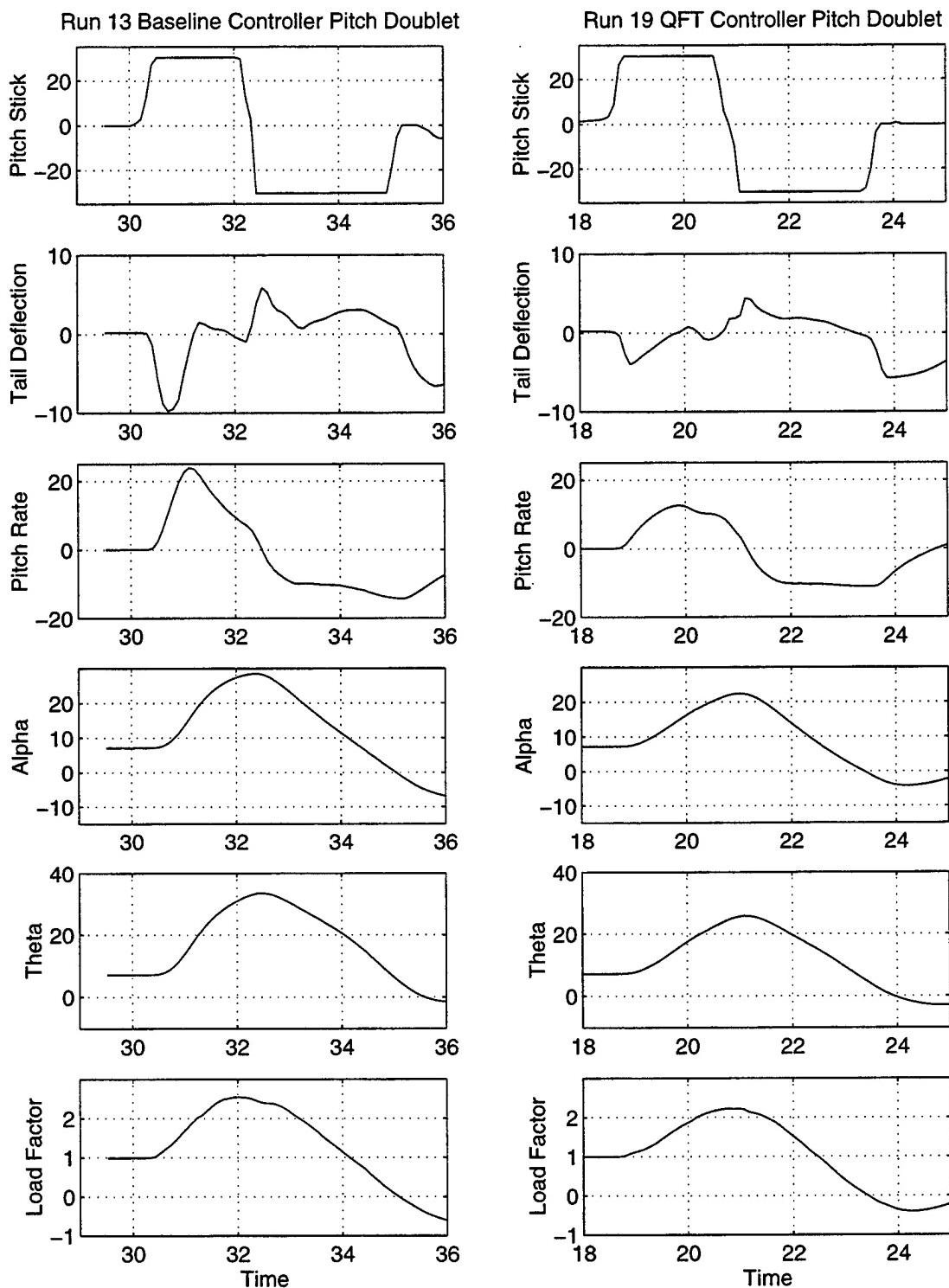


FIGURE C2. Pitch Doublet at Mach .7, 40,000 ft.

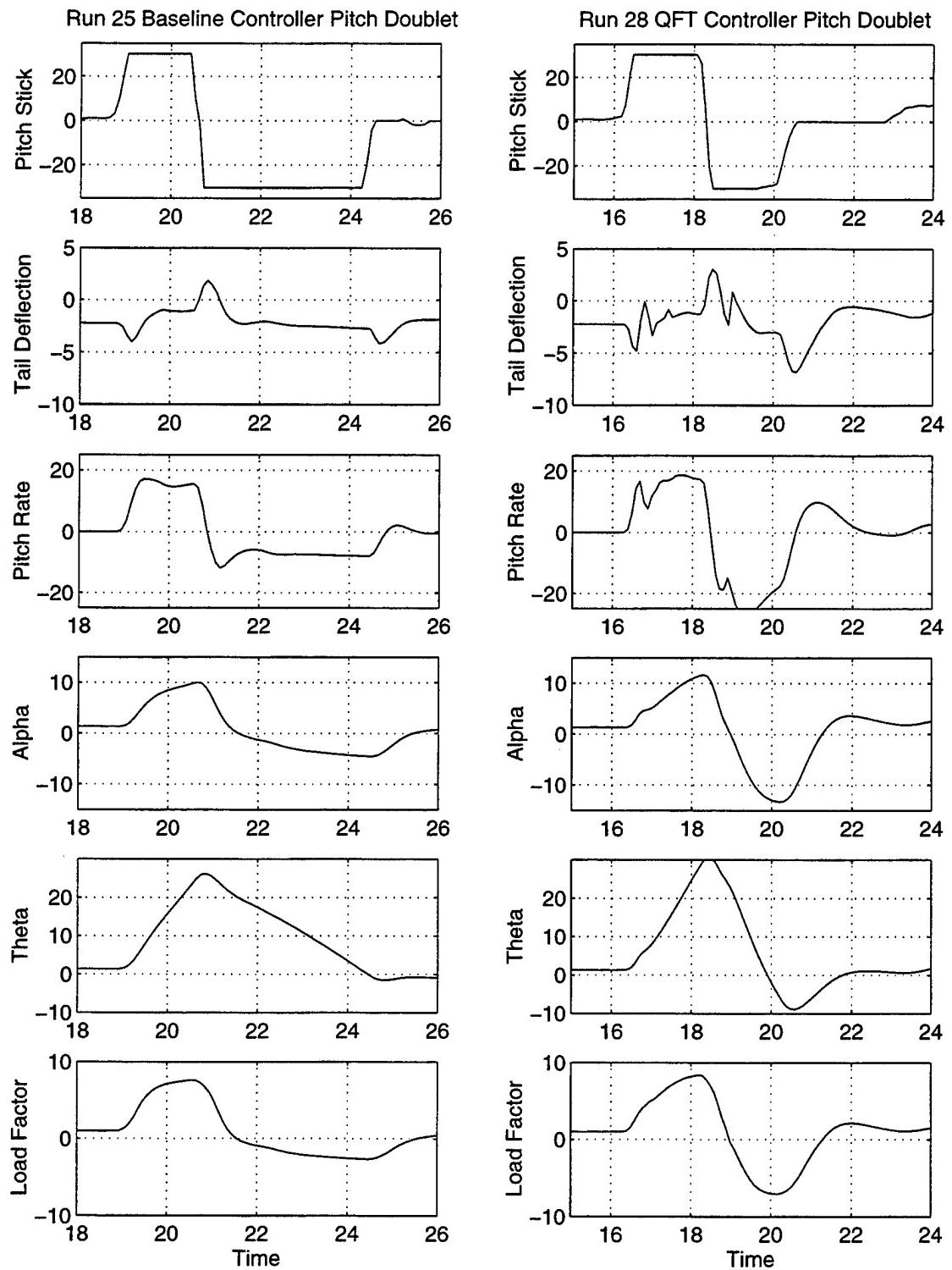


FIGURE C3. Pitch Doublet at Mach .9, 10,000 ft.

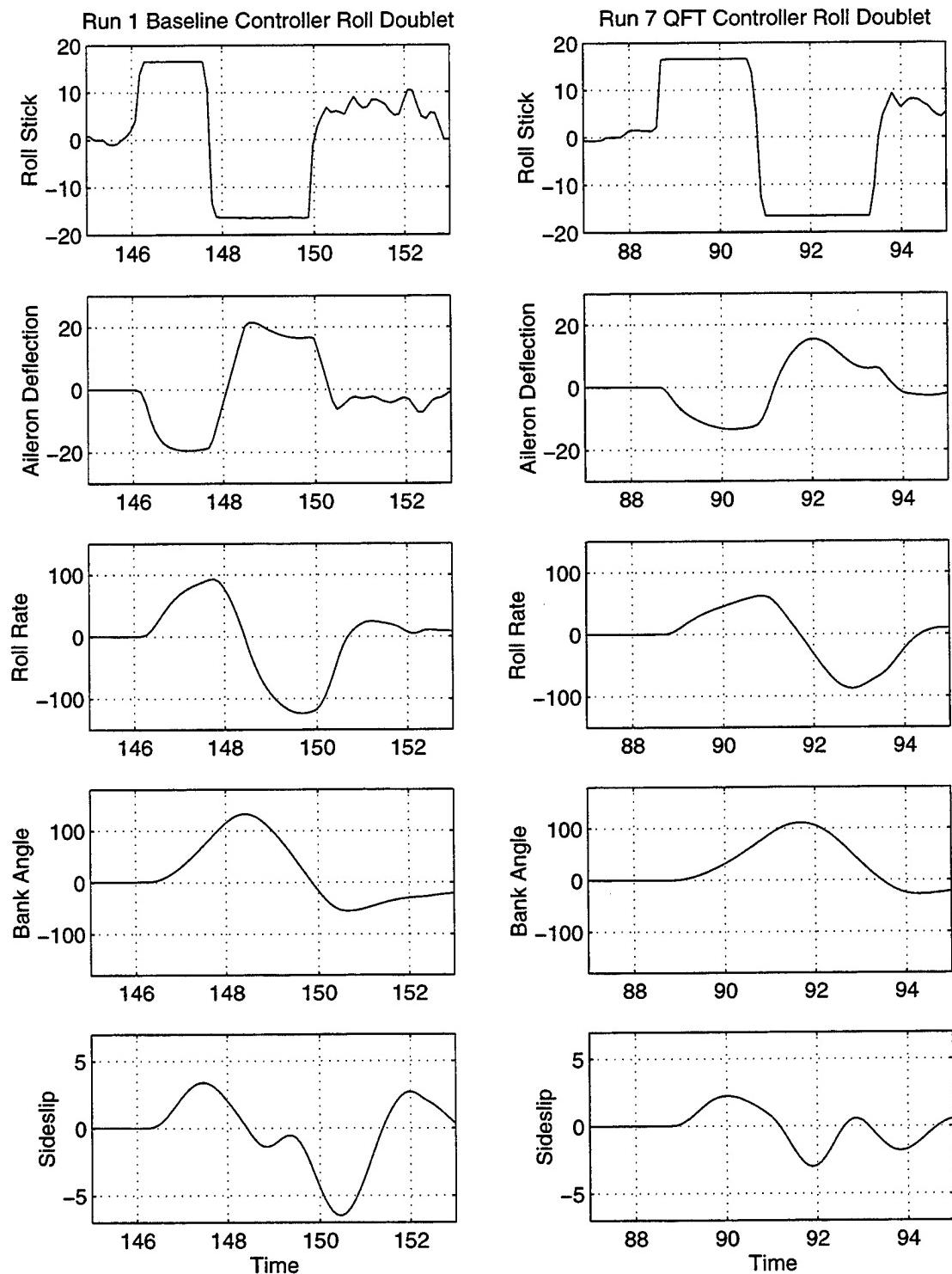


FIGURE C4. Roll Doublet at Mach .3, 10,000 ft.

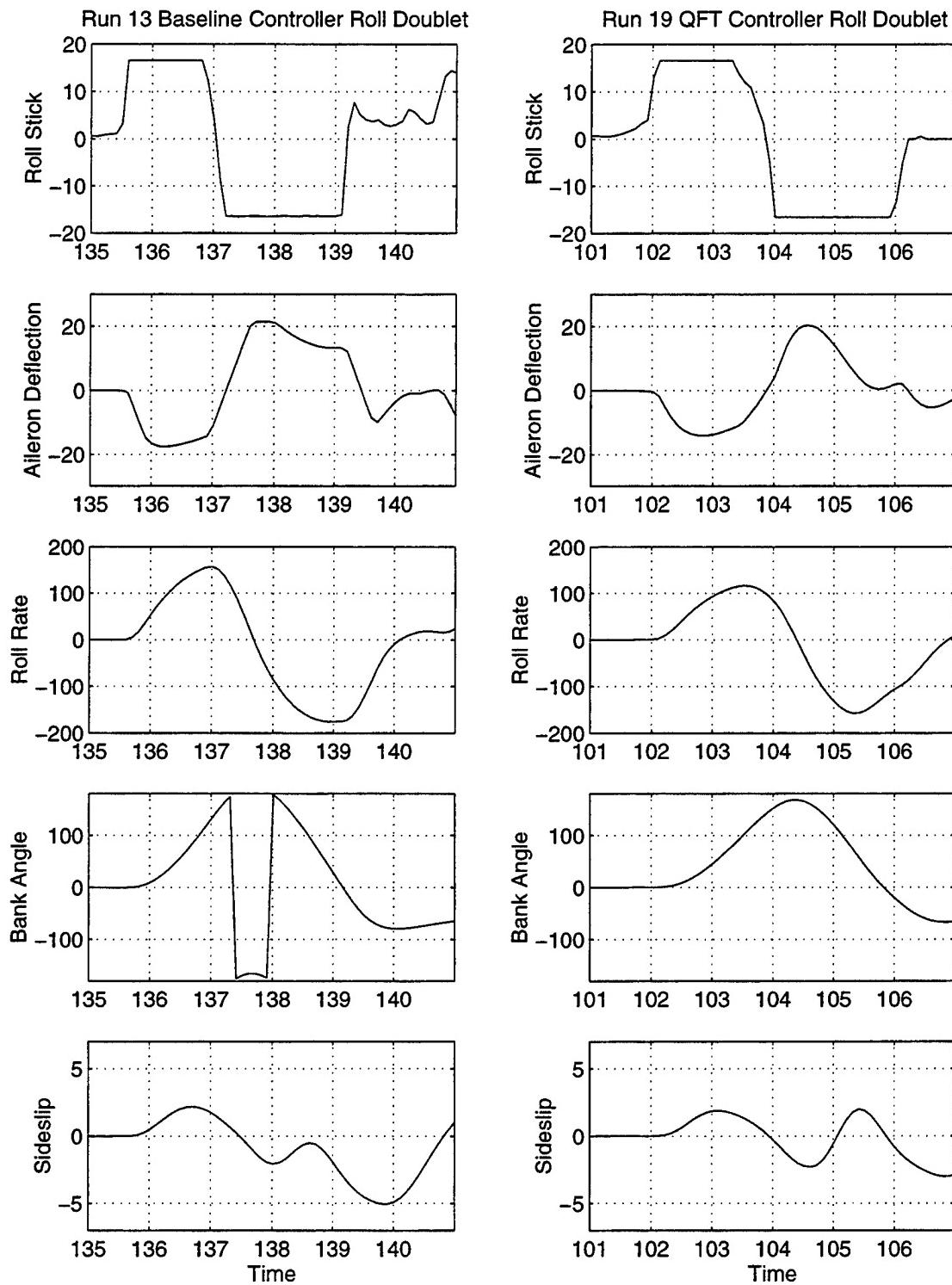


FIGURE C5. Roll Doublet at Mach .7, 40,000 ft.

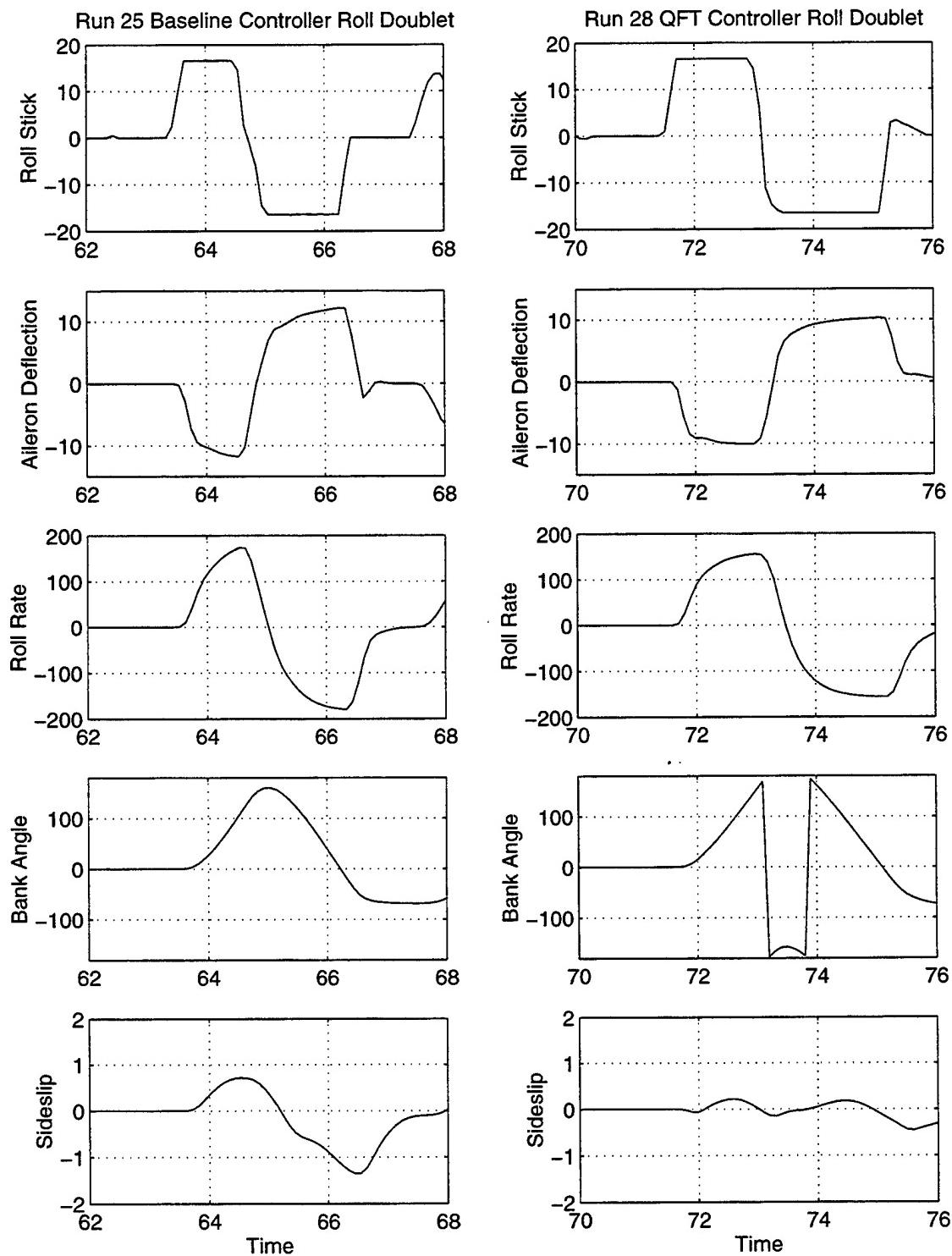


FIGURE C6. Roll Doublet at Mach .9, 10,000 ft.

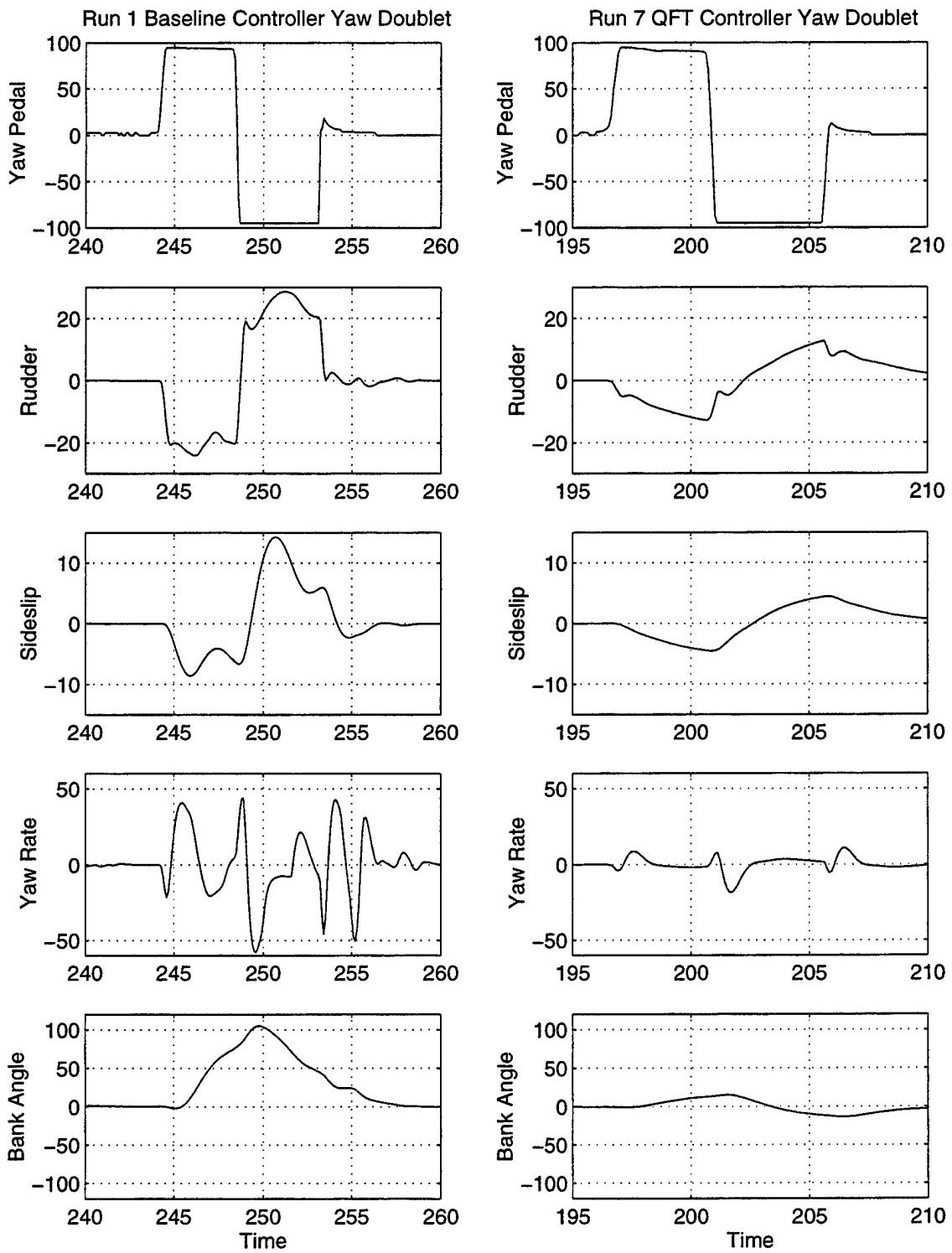


FIGURE C7. Yaw Doublet at Mach .3, 10,000 ft.

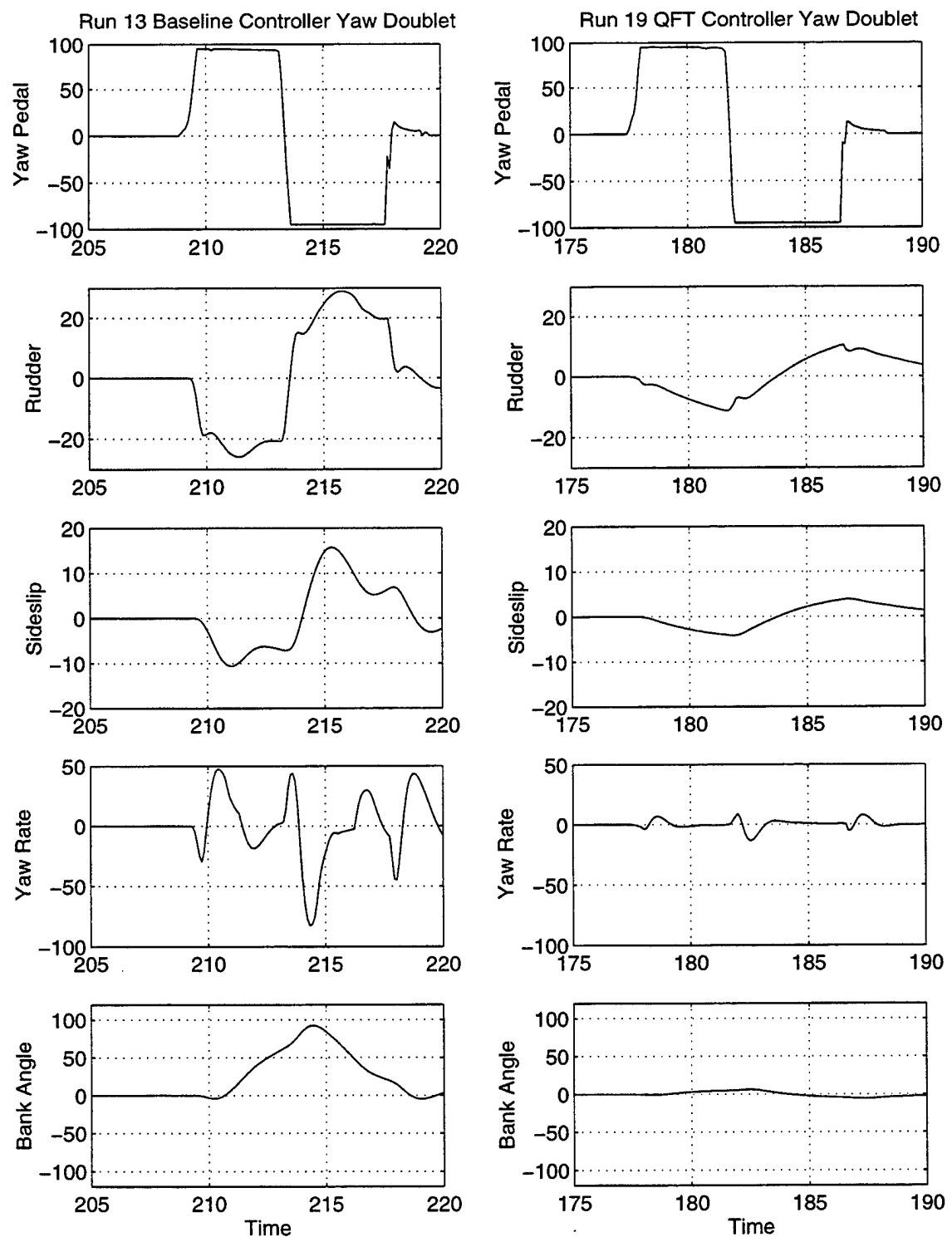


FIGURE C8. Yaw Doublet at Mach .7, 40,000 ft.

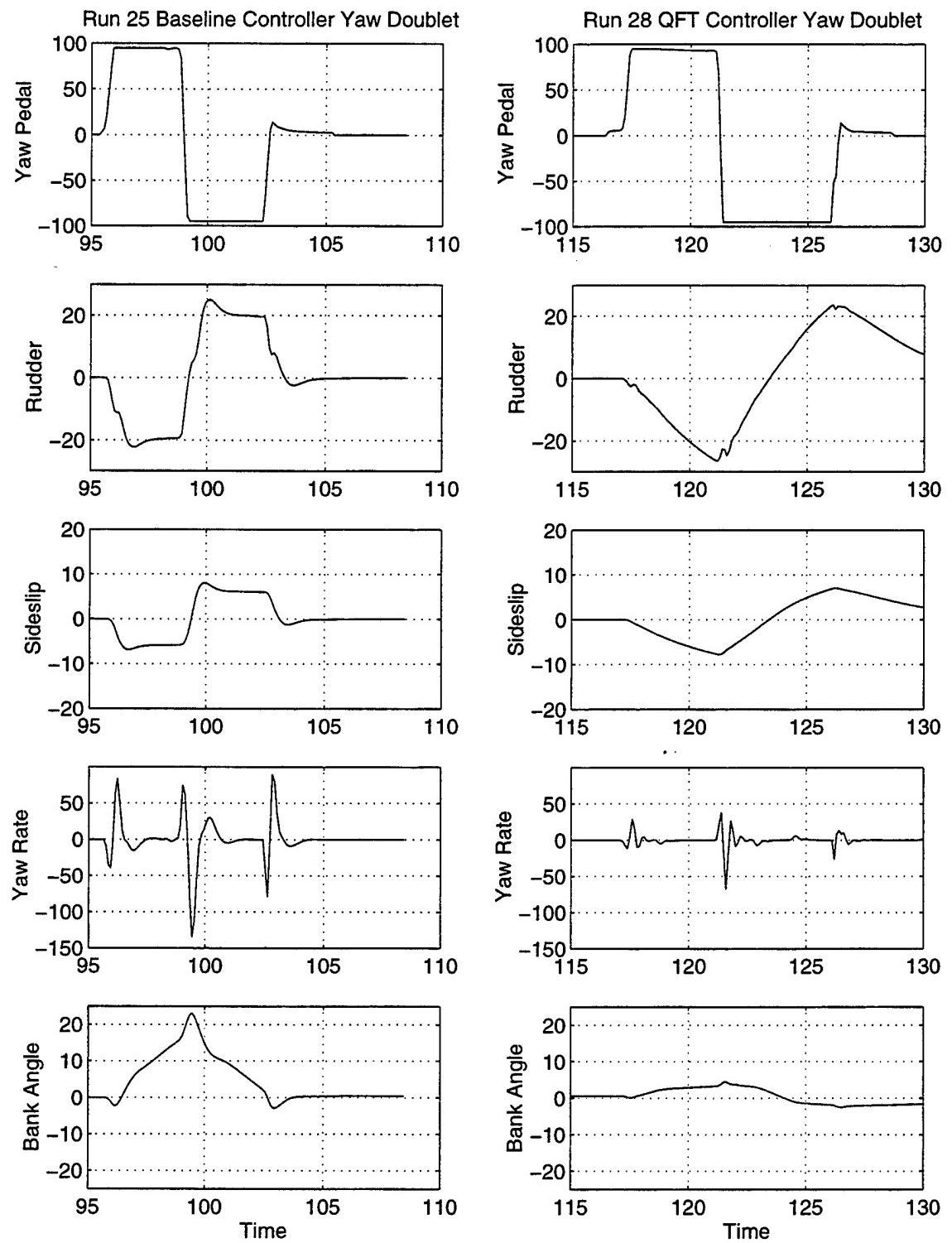


FIGURE C9. Yaw Doublet at Mach .9, 10,000 ft.

Appendix D

Loaded Roll Alpha/Beta Plots

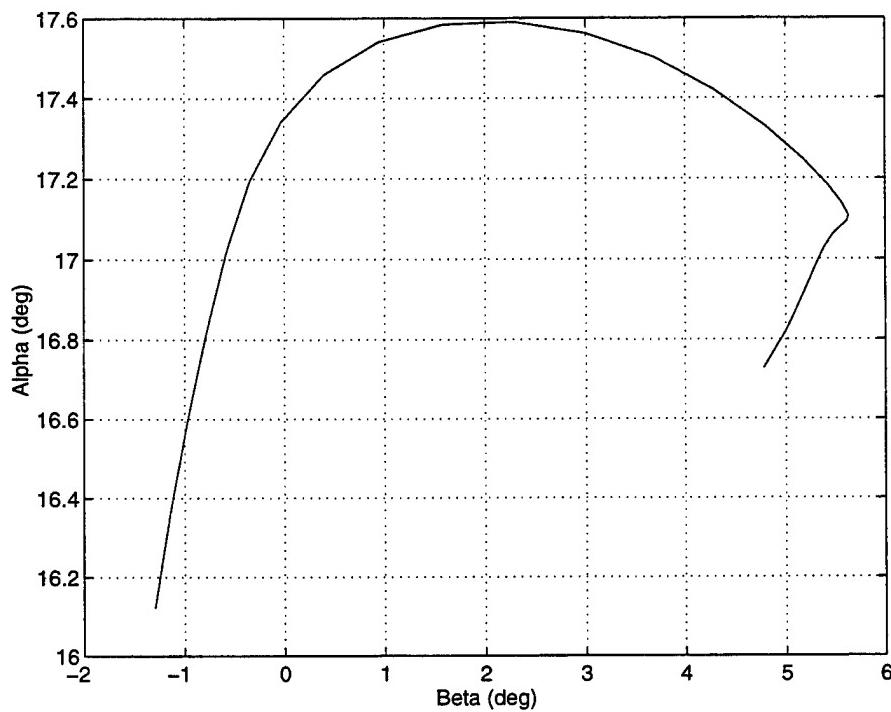


FIGURE D1. Baseline 15° α Loaded Roll at Mach .3, 12,500 ft.

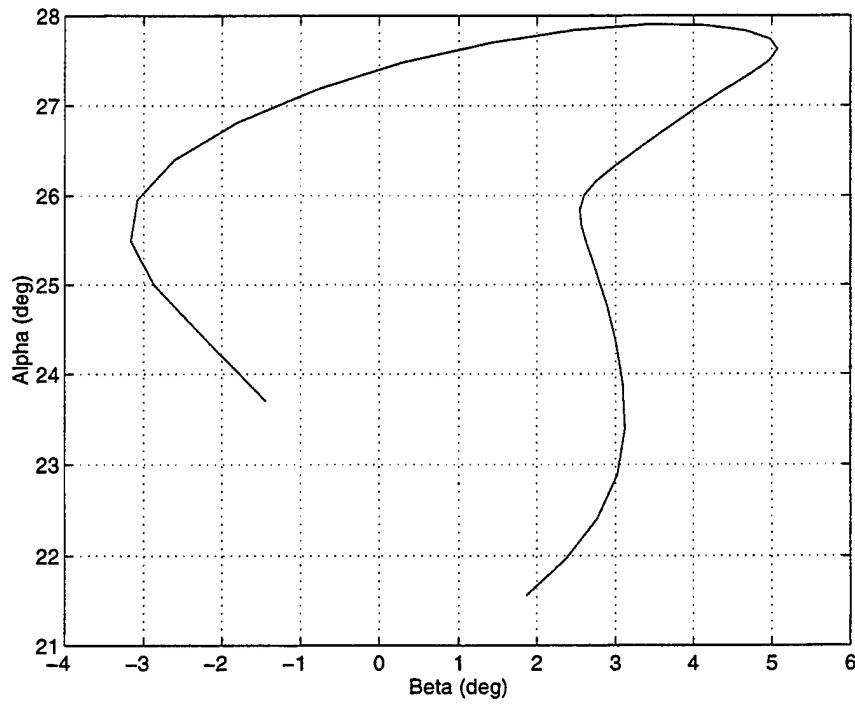


FIGURE D2. Baseline Max α Loaded Roll at Mach .3, 12,500 ft.

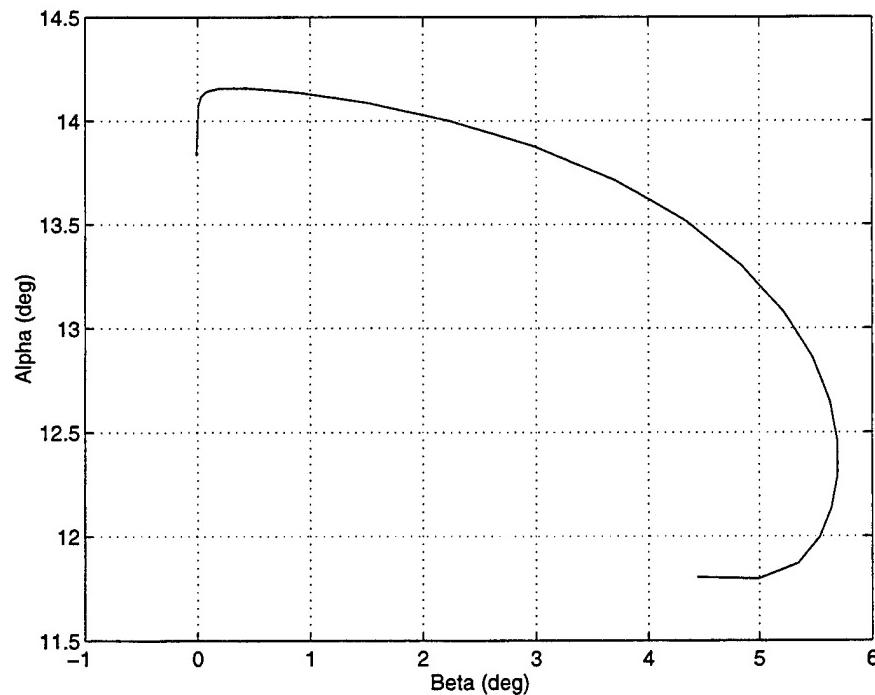


FIGURE D3. QFT FCS 15° α Loaded Roll at Mach .3, 12,500 ft.

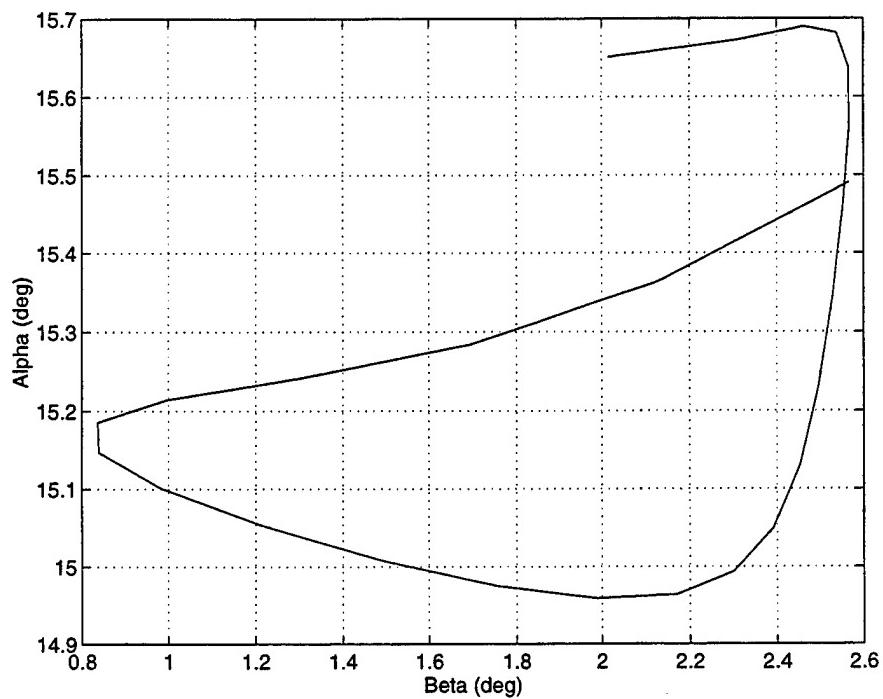


FIGURE D4. QFT FCS Max α Loaded Roll at Mach .3, 12,500 ft.

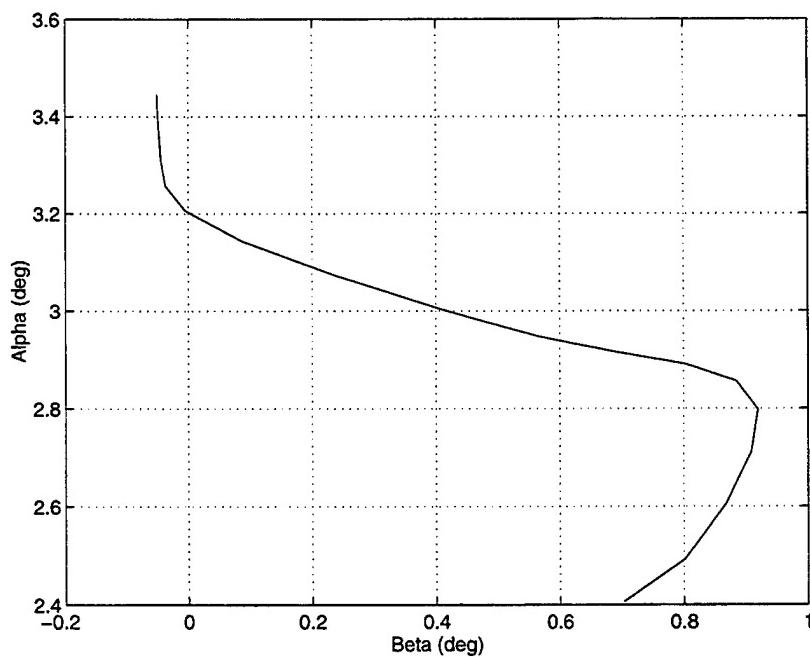


FIGURE D5. Baseline 3 G Loaded Roll at Mach .9, 10,000 ft.

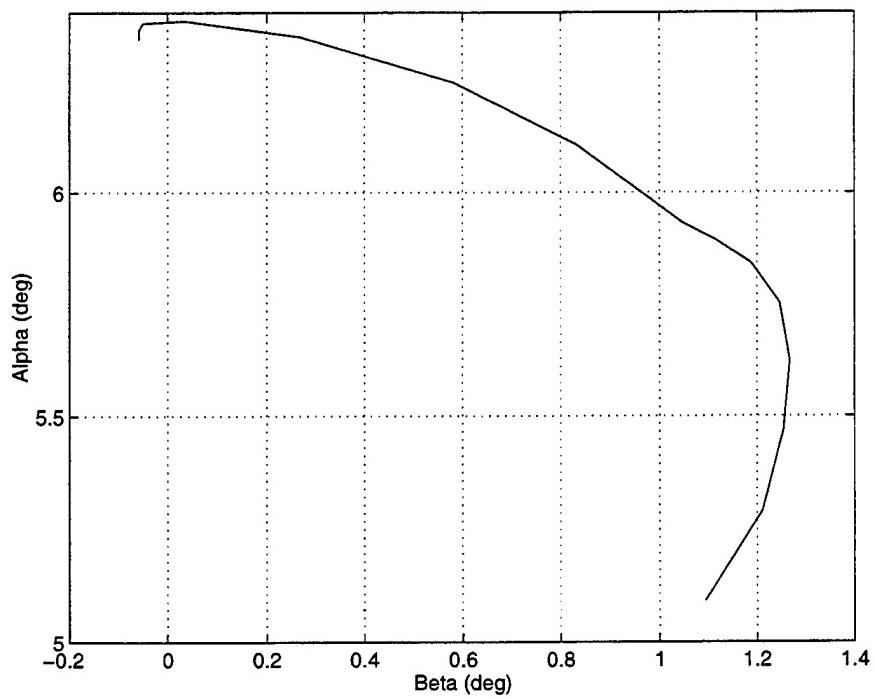


FIGURE D6. Baseline 6 G Loaded Roll at Mach .9, 10,000 ft.

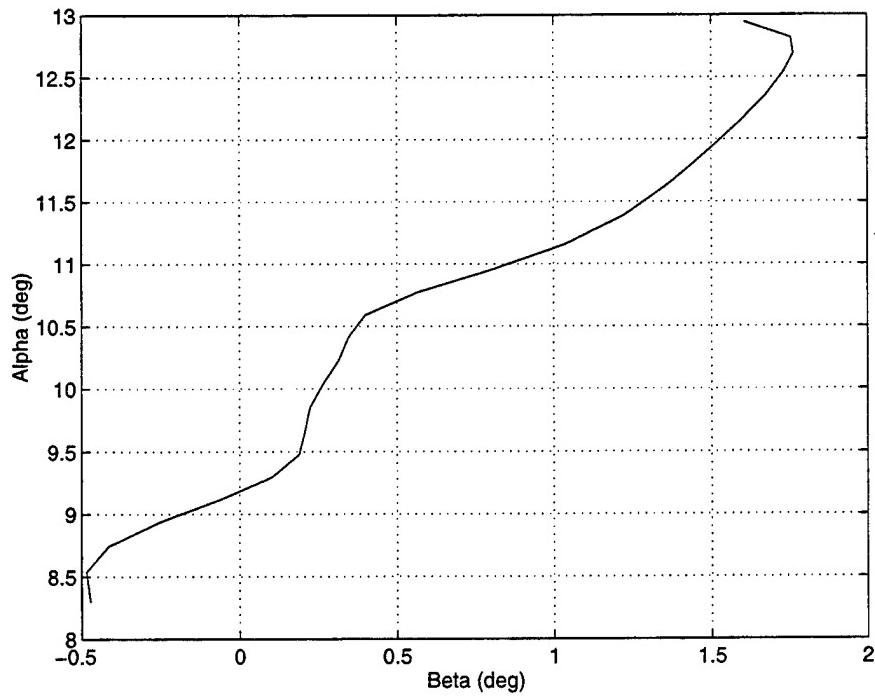


FIGURE D7. Baseline Max G Loaded Roll at Mach .9, 10,000 ft

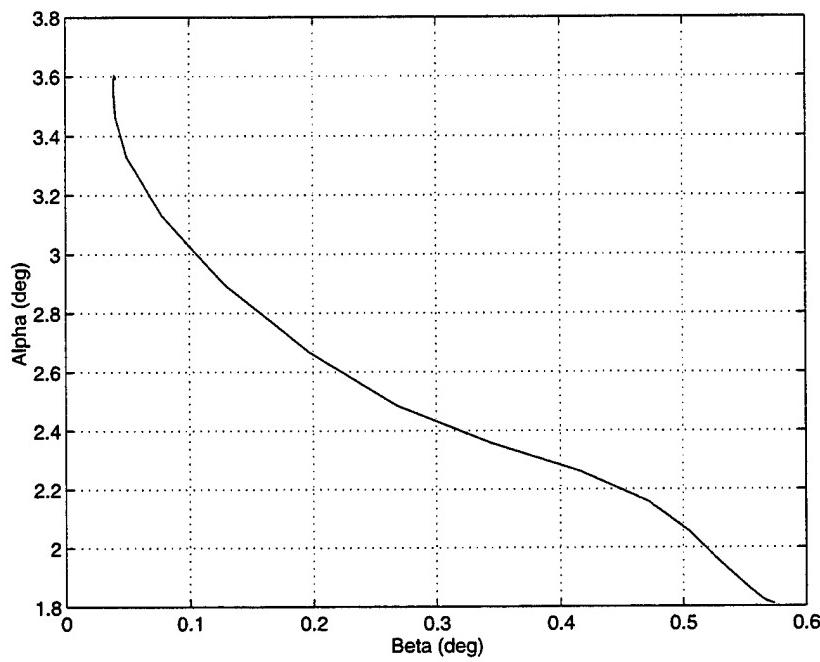


FIGURE D8. QFT FCS 3 G Loaded Roll at Mach .9, 10,000 ft.

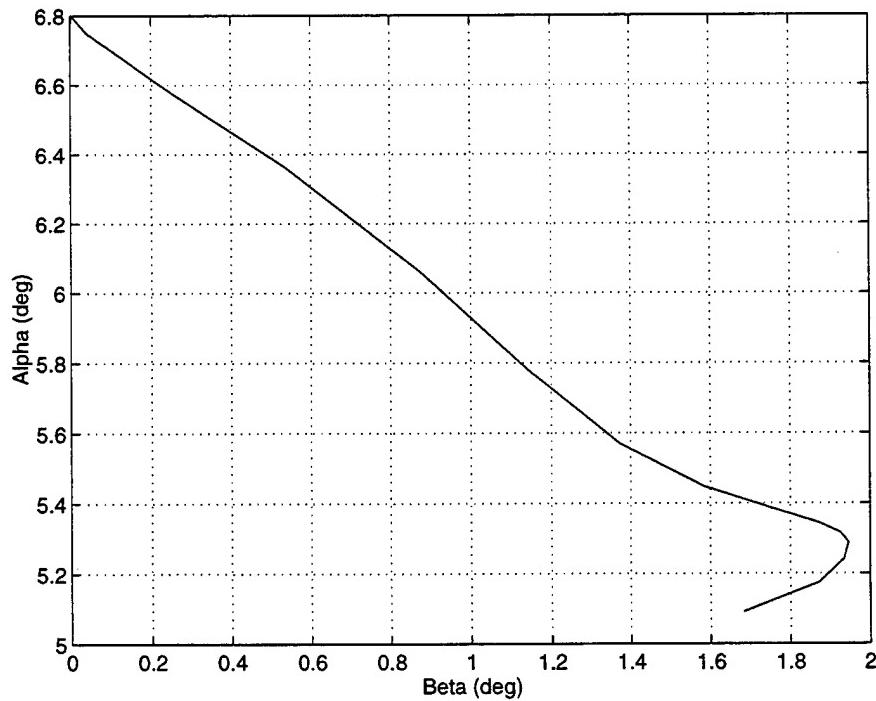


FIGURE D9. QFT FCS 6 G Loaded Roll at Mach .9, 10,000 ft.

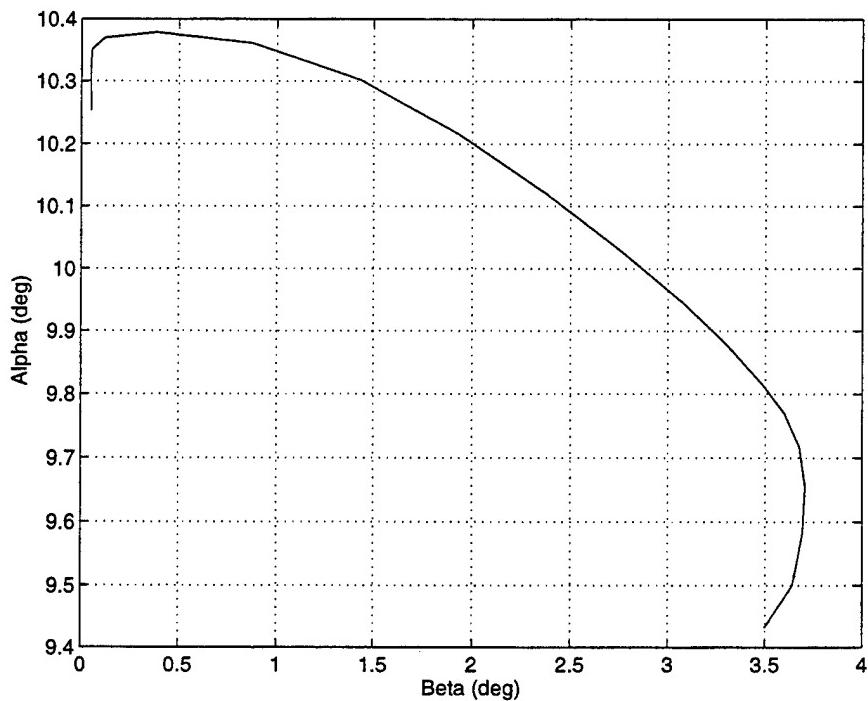


FIGURE D10. QFT FCS Max G Loaded Roll at Mach .9, 10,000 ft.

Appendix E

Angle Capture Maneuver Plots

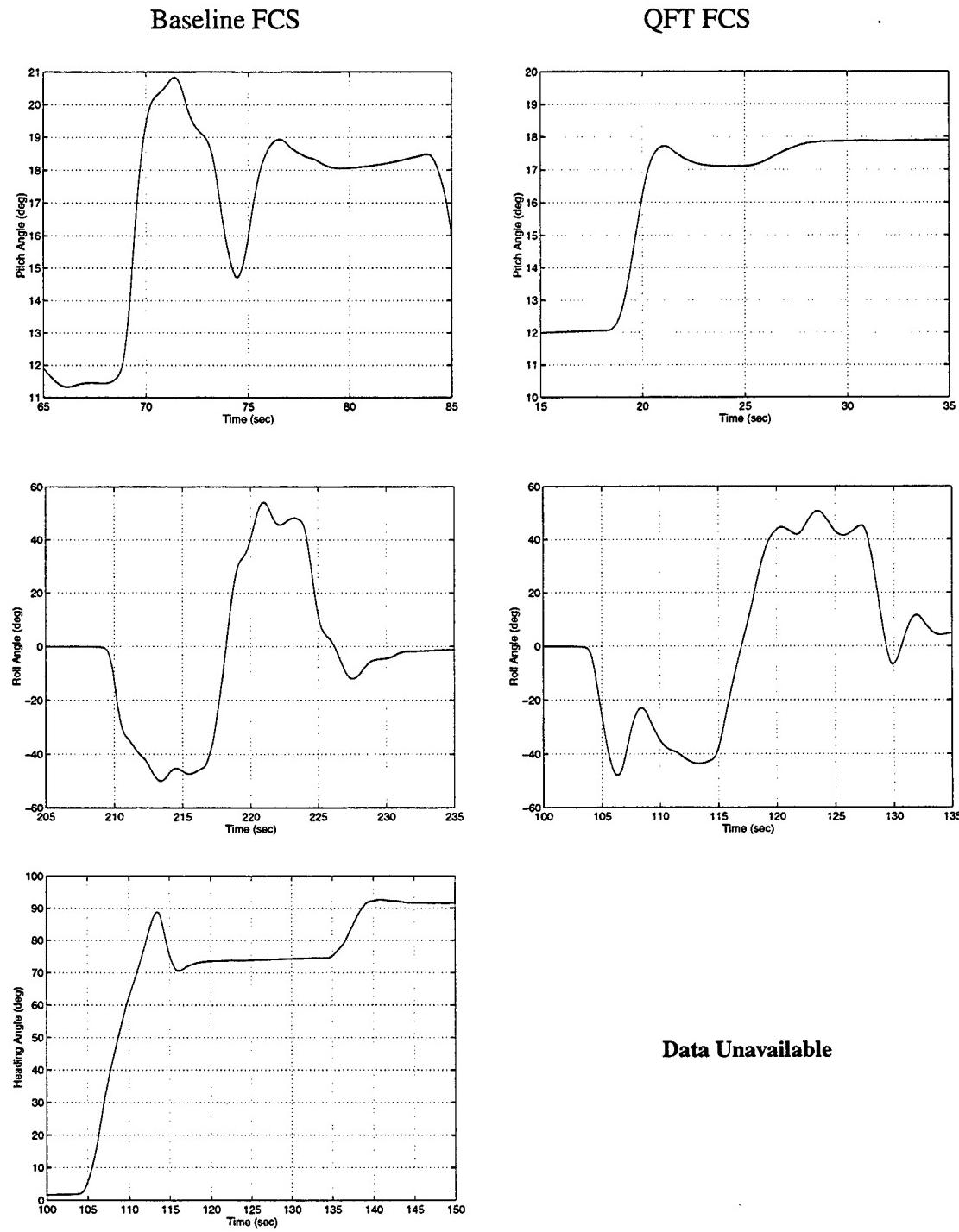


FIGURE E1. Angle Capture Maneuvers at Mach .3, 10,000 ft.

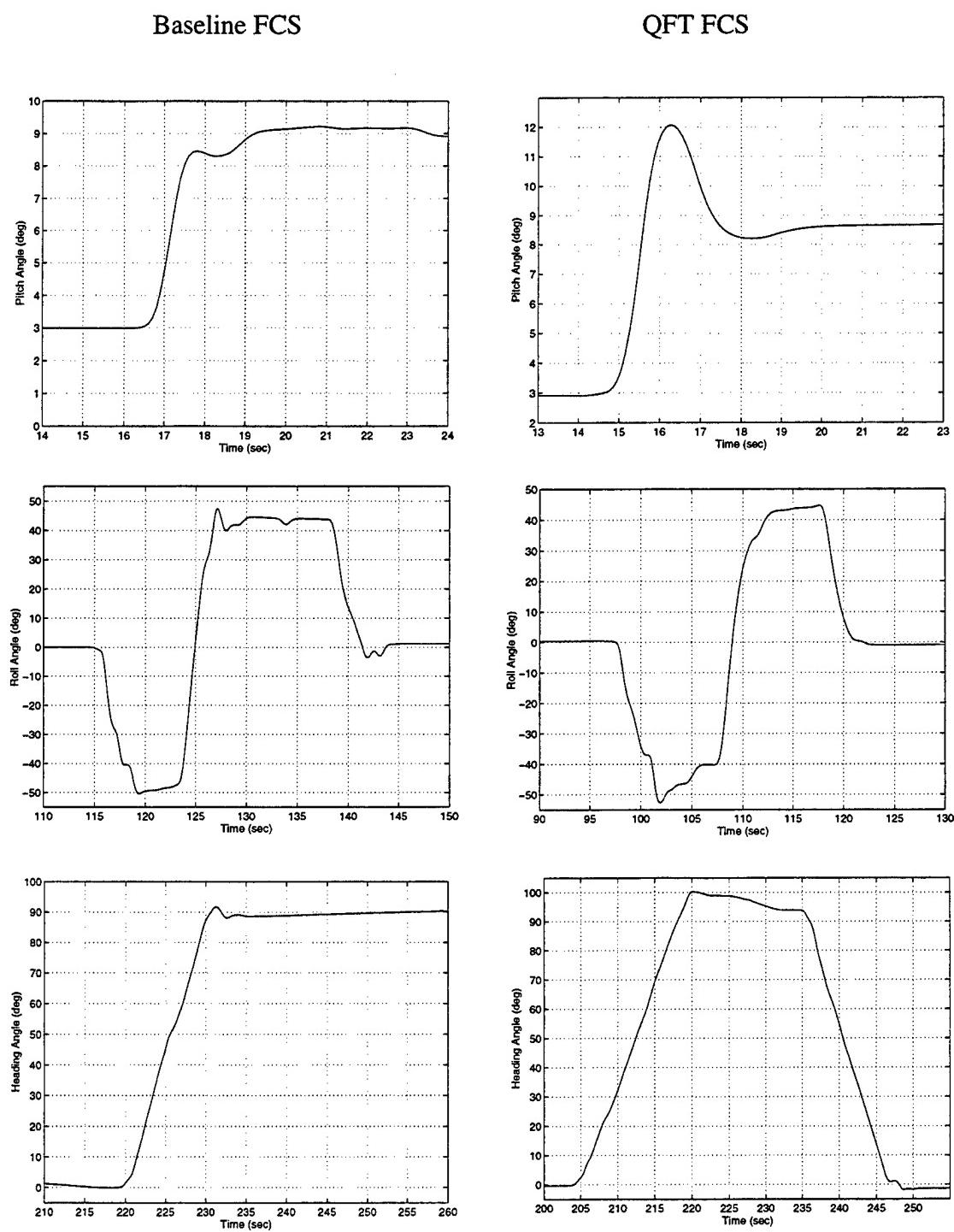
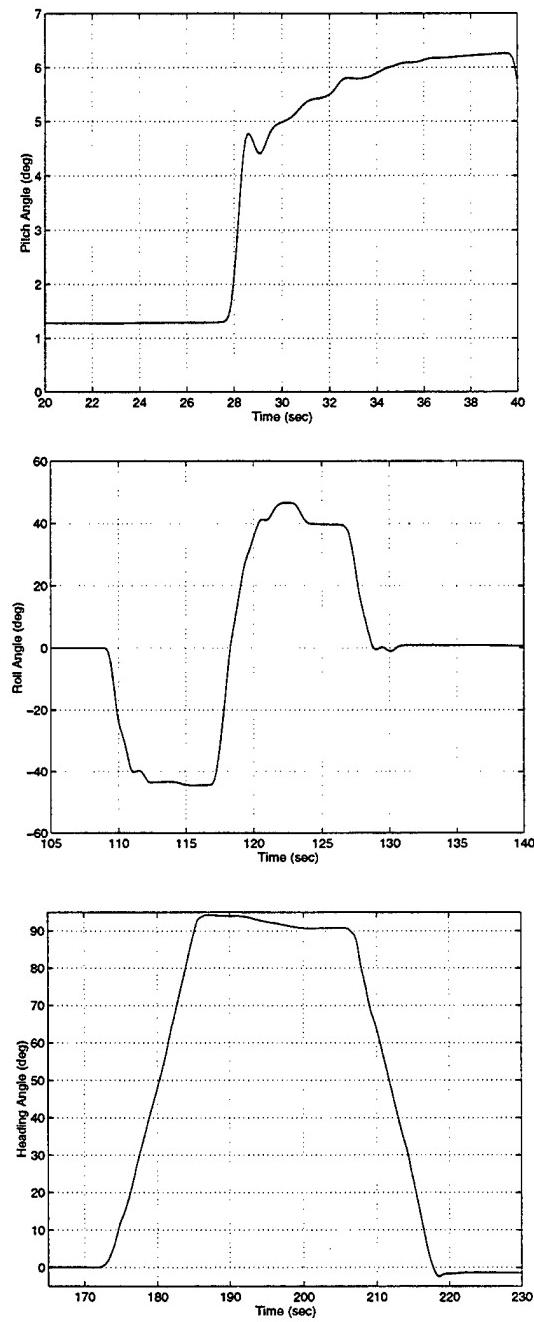


FIGURE E2. Angle Capture Maneuvers at Mach .6, 10,000 ft.

Baseline FCS



QFT FCS

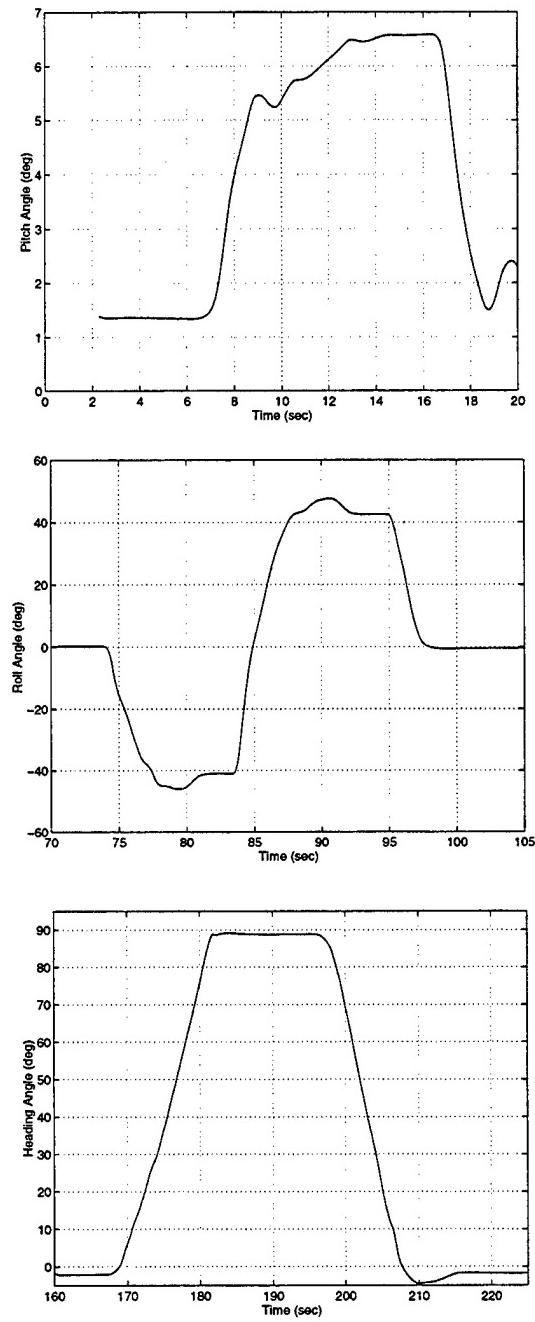


FIGURE E3. Angle Capture Maneuvers at Mach .9, 10,000 ft.

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